Switching Handbook

A Guide to Signal Switching in Automated Test Systems

6th **Edition**

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KEITHLEY

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Automated Test Systems

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Table of Contents

SECTION 1

The Switching Function

1.1   **Introduction**

Many electronic test systems use relay switching to connect multiple devices to sources and measurement instruments. In some cases, multiple sources and measuring instruments are connected to a single device. Switching allows automating the testing of multiple devices, thereby reducing error and costs.

Designing the switching for an automated test system demands an understanding of the signals to be switched and the tests to be performed. Test requirements can change frequently, so automated test systems should provide the flexibility needed to handle a variety of signals. Even simple test systems often have diverse and conflicting switching requirements.

The test definition will determine the system configuration and switching needs. Given the versatility that test systems must offer, designing the switching function may be one of the most complex and challenging parts of the overall system design. A basic understanding of relay types and switching configurations is helpful when choosing an appropriate switch system.

Section 1 describes the effects of switching on system performance. Relay types, switching configurations, and switching hardware options are also discussed.

1.2   **Effects of Switching on System Performance**

As a signal travels from its source to its destination, it may encounter various forms of interference or sources of error. Each time the signal passes through a connecting cable or switch point, the signal may be degraded. Careful selection of the switching hardware will maintain the signal integrity and the system accuracy.

Any switching element used in a test system should come as close to the ideal switch as possible. The ideal switch is one that:

• Has zero resistance when closed.

• Has infinite resistance when open.

• Is completely isolated from all other switches in the system.

• Is isolated from the drive control circuit.

• Takes no time to switch.

System designers must recognize, however, that real switches are not ideal, and that the relays themselves are typically mounted on printed circuit boards, which require the use of connectors and cables. The boards are often placed in a main-

frame that electronically controls the opening and closing of the relays. There-fore, when calculating the overall system accuracy, the engineer must include not only the effects of the switch itself, but all the switching hardware in the system.

For example, the offset current of the relays and the leakage resistance of the boards, connectors, and cables may degrade the integrity of high impedance applications. Contact potential and contact resistance of the relays can reduce the accuracy of low voltage and low resistance circuits. Switches may reduce the bandwidth of high frequency signals. Crosstalk between channels on the card may limit the low-level performance. The uncertainties that can occur will depend on the type of signals being switched.

System speed can also be a critical issue in system accuracy. For example, an erroneous reading will occur if a measurement is taken through a switch before the relay has had sufficient time to settle. Often, it's necessary to strike a compromise between system speed and accuracy. Factors that affect system speed include the triggering time of the hardware, the relay actuation and settling times, and software overhead.

Given the uncertainties associated with any new system design, switch hardware specifications must be reviewed carefully to make certain they fit the application. Section 3 provides a detailed description of switch card and mainframe specifications. The types of uncertainties that may arise in the system often depend on the type of signal being switched. Section 5 provides an overview of switching by signal type.

1.3 Switch Configurations and Conventions

An understanding of how relays are configured is critical to designing a switching system. Three terms are commonly used to describe the configuration of a relay: pole, throw, and form.

Pole refers to the number of common terminals within a given switch. *Throw* refers to the number of positions in which the switch may be placed to create a signal path or connection. These terms are best described by illustration.

Figure 1-1a shows single-pole, single-throw normally-open switch (SPST NO), while **Figure 1-1b** shows a single-pole, double-throw (SPDT) switch. One terminal is normally-open (NO) and the other is normally-closed (NC). Depending on the state of the switch, one or the other position is connected to the common terminal (COM). One signal path is broken before the other is connected, which is why this is referred to as a break-before-make configuration.

When more than one common terminal is used, the number of poles increases. **Figure 1-1c** shows a double-pole, single-throw (DPST) switch. Both poles are actuated simultaneously when the relay is energized. In this case, both poles are either always closed or always open. **Figure 1-1d** shows a double-pole, double-throw (DPDT) switch.

Contact form, or simply *form*, is another term that relay manufacturers often use to describe a relay's contact configuration. "Form A" refers to a single-pole, normally-open switch. "Form B" indicates a single-throw, normally-closed switch, and "Form C" indicates a single-pole, double-throw switch. Virtually any contact configuration can be described using this format. **Figure 1-1a**, for instance, is a single "Form A" switch, while **Figure 1-1d** is a dual "Form C" switch.
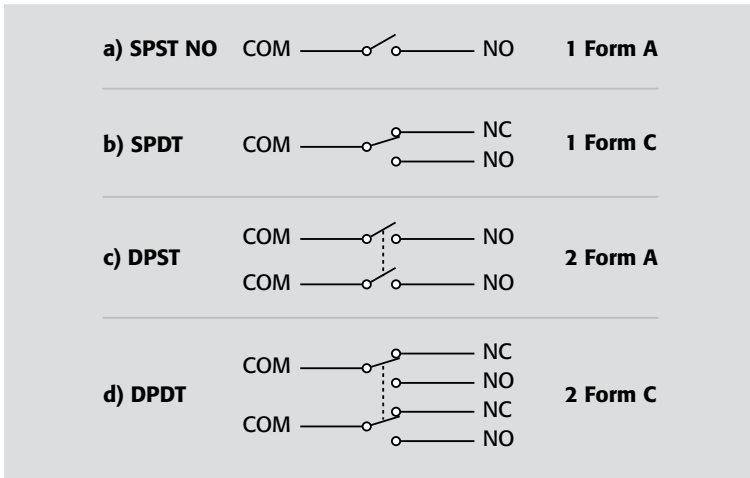
Figure 1-1. Relay type schematics

1.4   Switching Topologies

This section describes the various types of switching configurations available: scanner, multiplex, matrix, isolated, and RF switching. The examples provided might provide some guidance when determining which configuration is best for a particular application.

1.4.1 Scanner Switching

The scan configuration or scanner is the simplest arrangement of relays in a switch system. As shown in **Figure 1-2**, it can be thought of as a multiple position selector switch.
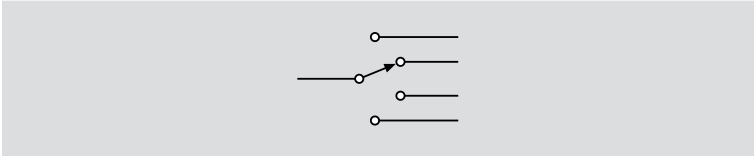
Figure 1-2. Scanner – a one out of n selector switch

The scanner is used to connect multiple inputs to a single output in sequential order. Only one relay is closed at any time. In its most basic form, relay closure proceeds from the first channel to the last. Some scanner systems have the capability to skip channels.

Figure 1-3 illustrates an example of a scan configuration. In this diagram, the battery is connected to only one lamp at a time, such as in an elevator's floor indicator system. Another example is a scanner for monitoring temperatures at several locations using one thermometer and multiple sensors. Typical uses of scanner switching include burn-in testing of components, monitoring time and temperature drift in circuits, and acquiring data on system variables such as temperature, pressure, and flow.
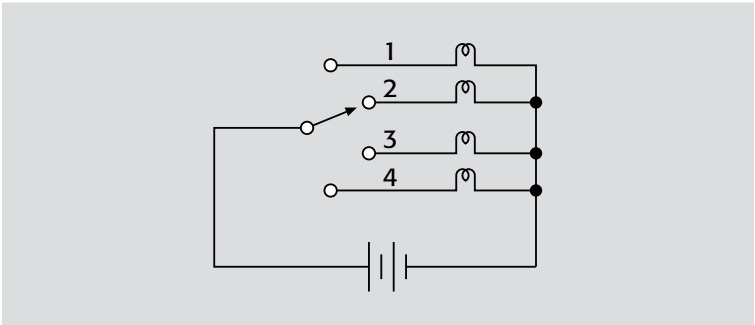
Figure 1-3. Scanner to indicate elevator location

1.4.2 Multiplex Switching

Like the scan configuration, multiplex switching can be used to connect one instrument to multiple devices (1:N) or multiple instruments to a single device (N:1). However, the multiplex configuration is much more flexible than the scanner. Unlike the scan configuration, multiplex switching permits:

• Multiple simultaneous connections.

• Sequential or non-sequential switch closures.

One example of a multiple closure would be to route a single device output to two instruments, such as a voltmeter and a frequency counter. **Figure 1-4** illustrates another example of multiplex switching. This diagram shows measuring the insulation resistance between any one pin and all other pins on a multipin connector. To measure the insulation resistance between pin 1 and all other pins (2 and 3), close Chs. 2, 3, and 4. This will connect the ammeter to pin 1 and the voltage source to pins 2 and 3. The insulation resistance is the combination of R_{1-2} and R_{1-3} in parallel as shown. Note that in this application, more than one channel is closed simultaneously in non-sequential order. Typical applications of multiplex switching include capacitor leakage, insulation resistance, and contact resistance test systems for multiple devices.
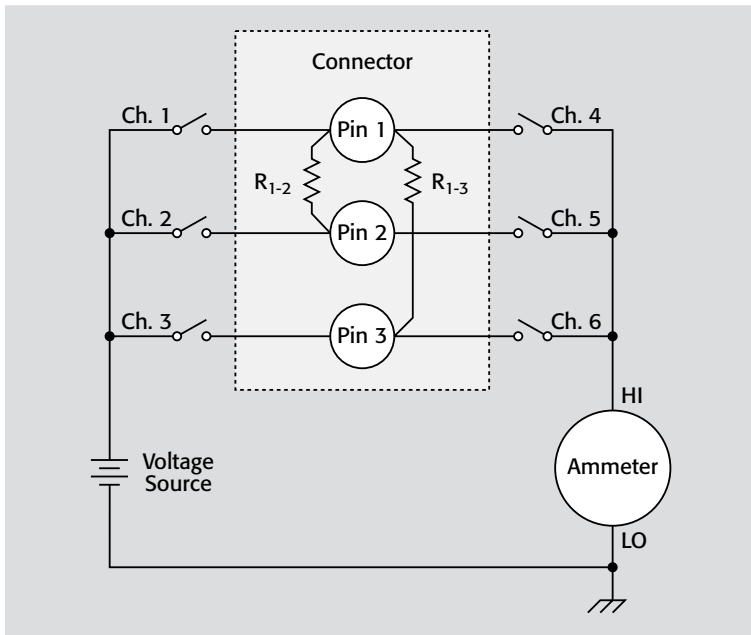
Figure 1-4. Multiplex switching used to test the insulation resistance of multipin connector

1.4.3 Matrix Switching

The matrix switch configuration is the most versatile because it can connect multiple inputs to multiple outputs. A matrix is useful when connections must be made between several signal sources and a multipin device, such as an integrated circuit or resistor network.

Using a matrix switch card allows connecting any input to any output by closing the switch at the intersection (crosspoint) of a given row and column. The most common terminology to describe the matrix size is M rows by N columns (M×N). For example, a 4×10 matrix switch card, such as the Keithley Model 7012, has four rows and ten columns. Matrix switch cards generally have two or three poles per crosspoint.

As shown in **Figure 1-5**, a 5VDC source can be connected to any two terminals of the device under test (DUT). A function generator supplies pulses between another two terminals. Operation of the DUT can be verified by connecting an oscilloscope between yet another two terminals. The DUT pin connections can easily be programmed, so this system will serve to test a variety of parts.
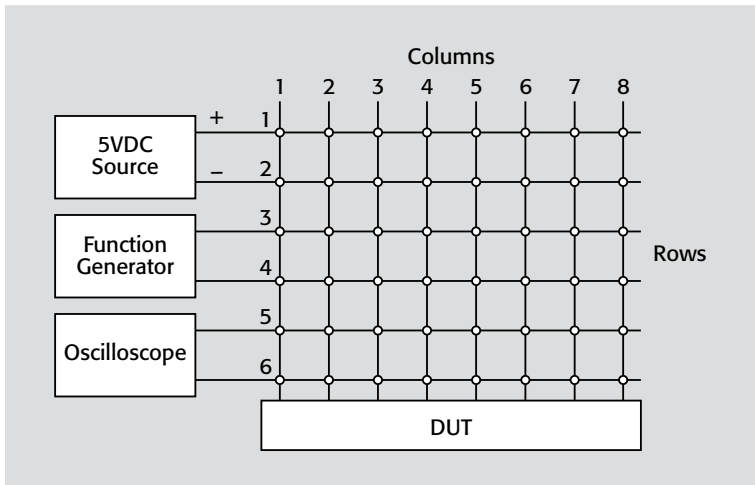
Figure 1-5. 6×8 one-pole matrix example

When choosing a matrix card for use with mixed signals, some compromises may be required. For example, if both high frequency and low current signals must be switched, take extra care when reviewing the specifications of the card. The card chosen must have wide bandwidth as well as good isolation and low offset current. A single matrix card may not satisfy both requirements completely, so the user must decide which switched signal is more critical.

In a system with multiple cards, card types should not be mixed if their outputs are connected together. For example, a general-purpose matrix card with its output connected in parallel with a low current matrix card will degrade the performance of the low current card.

Examples of matrix cards include:

Mainframe	Matrix Cards
2700, 2701, 2750	7709
7001, 7002	7012, 7019-C, 7152, 7153
7002-HD	7002-HD-MTX1
707A, 708A	7071, 7071-4, 7072, 7072-HV, 7173-50, 7174A
3706	3730

Matrix Expansion

A large system may require more rows and/or columns than a single card can provide. A matrix can be expanded by joining the rows and/or columns of several cards together. For example, **Figure 1-6** shows how the number of columns can be expanded by using two Model 3730 cards to make a 6×32 matrix. Three cards will make a 6×48 matrix, and so on. Depending upon the switch card and mainframe, the rows of the cards may be connected together through the backplane of the mainframe or the rows may be connected externally. The rows of the Model 3730 cards can be connected through the analog backplane of the Series 3700 System Switch/Multimeter. When using multiple matrix cards, check the specifications to determine if the rows can be connected through the backplane or if they must be wired externally.
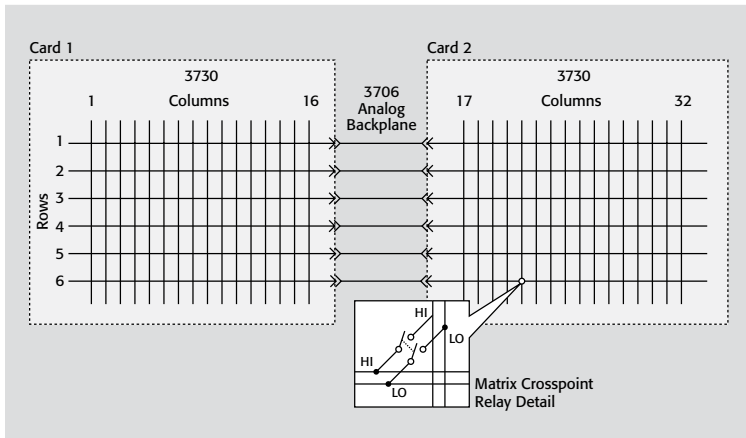
Figure 1-6. 6×32 two-pole matrix

Figure 1-7 shows an example of matrix card rows connected by on-board coaxial jumpers. Up to six Model 3730 matrix cards can be connected in this manner in a Model 3706-S mainframe. With instruments and DUTs both connected to

columns, two crosspoints must be closed for each signal path, increasing the safety factor.

The figure shows closed crosspoints for biasing the gate of DUT#1 by one of the SMUs of a Model 2636 System SourceMeter Instrument and applying V_{DS} to DUT#1 by the other SMU in the same Model 2636. The guard pathways of the matrix cards extend driven guard of the SMUs to the DUTs to eliminate the effects of leakage current.
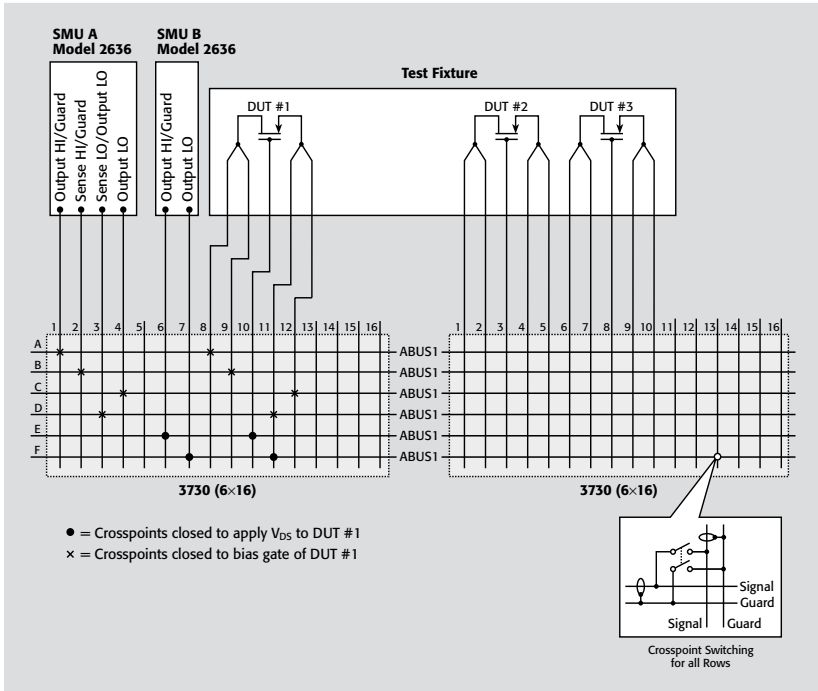
Figure 1-7. 6×16 matrix with instruments and DUTs

When working with Series 7000 mainframes, to increase the number of rows, the columns of the cards must be connected together externally. For example, **Figure 1-8** shows two Model 7012 4×10 cards connected to form an 8×10 two-pole matrix.

In some cases, both the rows and columns must be expanded. For example, an 8×20 matrix can be configured using four of the 4×10 cards, as in **Figure 1-9**. If using Model 7012 cards, only the rows are connected through the backplane. The columns must be wired together externally.
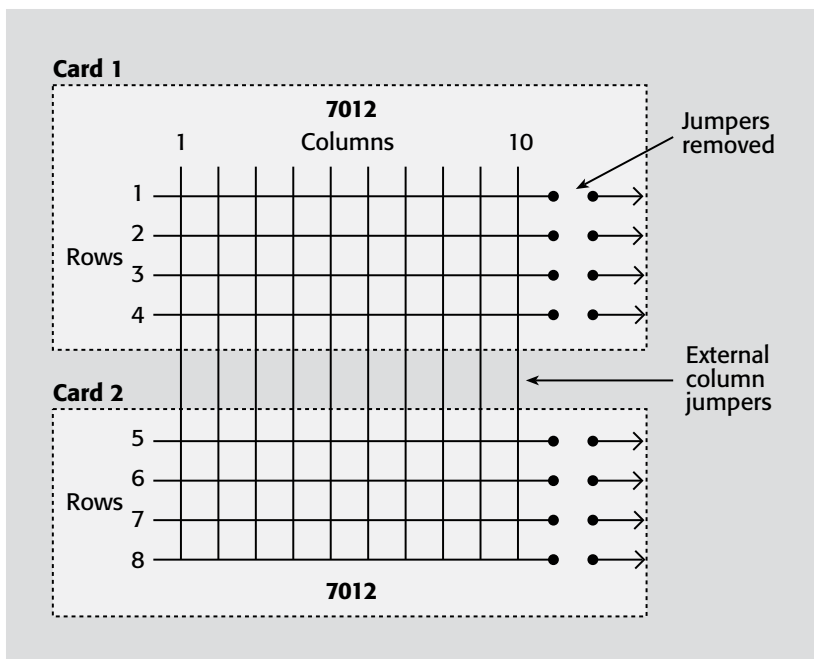
Figure 1-8. 8×10 matrix
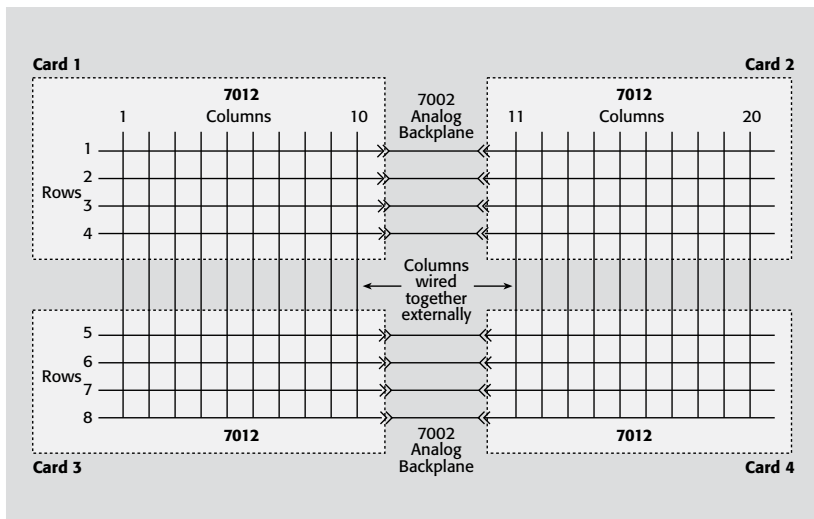
Figure 1-9. 8×20 matrix

1.4.4 Isolated Switching

The isolated, or independent, switch configuration consists of individual relays, often with multiple poles, with no connections between relays. **Figure 1-10** represents a single isolated relay or actuator. In this diagram, a single-pole normally open relay is controlling the connection of the voltage source to the lamp. This relay connects one input to one output. An isolated relay can have more than one pole and can have normally closed contacts as well as normally open contacts.
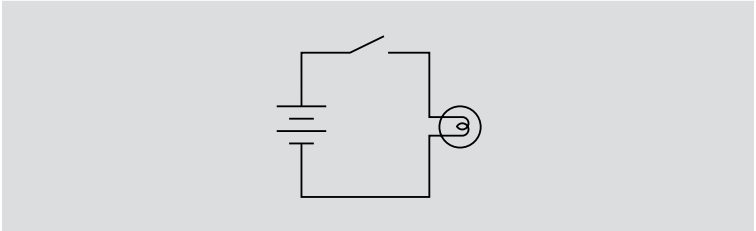
Figure 1-10. Single isolated switch

Given that the relays are isolated from each other, the terminals of each channel on the switch card are independent from the terminals of the other channels. As shown in **Figure 1-11**, each isolated Form A relay has two terminals. Two-pole isolated relays would have four terminals (two inputs and two outputs). A Form C isolated relay would have three terminals.
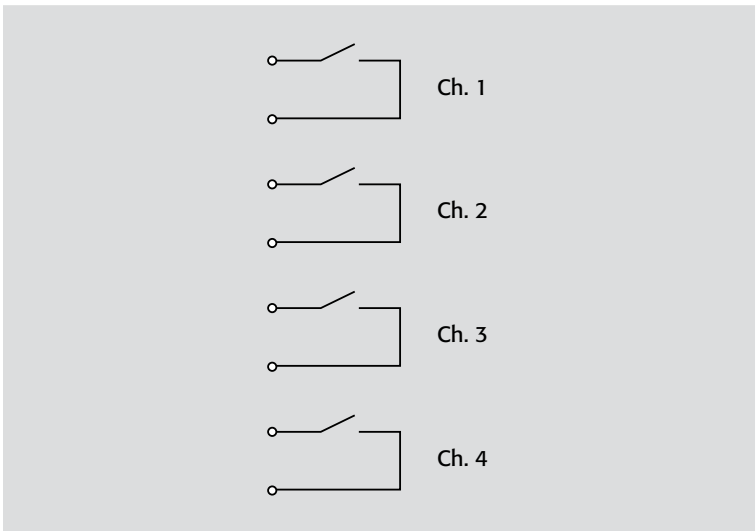
Figure 1-11. Isolated relays on a switch card

Isolated relays are not connected to any other circuit, so the addition of some external wiring makes them suitable for building very flexible and unique combinations of input/output configurations. Isolated relays are commonly used in power and control applications to open and close different parts of a circuit that are at substantially different voltage levels. Applications for isolated relays include controlling power supplies, turning on motors and annunciator lamps, and actuating pneumatic or hydraulic valves.

Keithley Models 7001/7002 family switch cards with isolated relays include the Models 7013, 7037, 7166, 7169A, and 7036. The Model 7705 card for the Models 2700/2701/2750 Integra Multimeter/Data Acquisition/Switch Systems provides 40 isolated relays.

1.4.5 RF Switching: Cascade, Tree, and Matrix Switching

RF (or microwave) signals have switching considerations that differ from those for DC or low frequency AC signals. Some of these considerations include insertion loss, crosstalk, propagation delay, and unterminated stubs. As a result, switching configurations for RF signals are designed to minimize signal losses and maintain a characteristic impedance through the system. Cascade, tree, or matrix switching configurations can be implemented for microwave signal routing.

Cascade

The cascade switching configuration is used to connect one instrument to one of many devices or test points with minimal impedance discontinuity. This is important primarily at frequencies of 10MHz and higher to prevent unwanted signal reflections. Such reflections will create errors in amplitude measurements. Actuation of any one relay disconnects all other devices from the source, as shown in **Figure 1-12**. In this example, if Channel 1 (Ch. 1) is actuated, a constant impedance path is established from the source to Device 2. All the other devices are isolated from this path. With two cascade switch banks, both source and measure connections can be made to each DUT.

The advantages of the cascade configuration include the fact that there are no unterminated stubs and the configuration is easily expandable. A disadvantage of the cascade configuration is that the signal may pass through more than one switch contact to the device under test, causing higher losses in the signal. The propagation delay will grow with increasing path length.

Tree

The tree switch configuration shown in **Figure 1-13** is an alternative to the cascade configuration. When compared to the cascade configuration, the tree
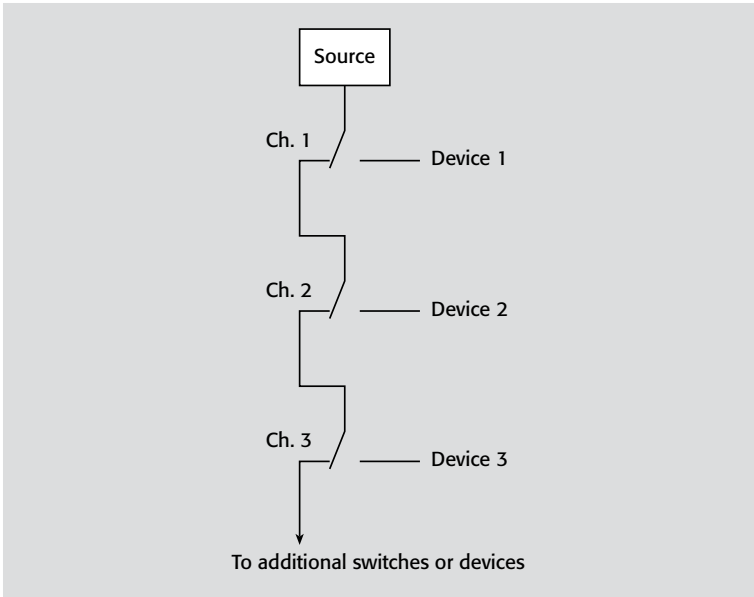
Figure 1-12. Cascade switching configuration
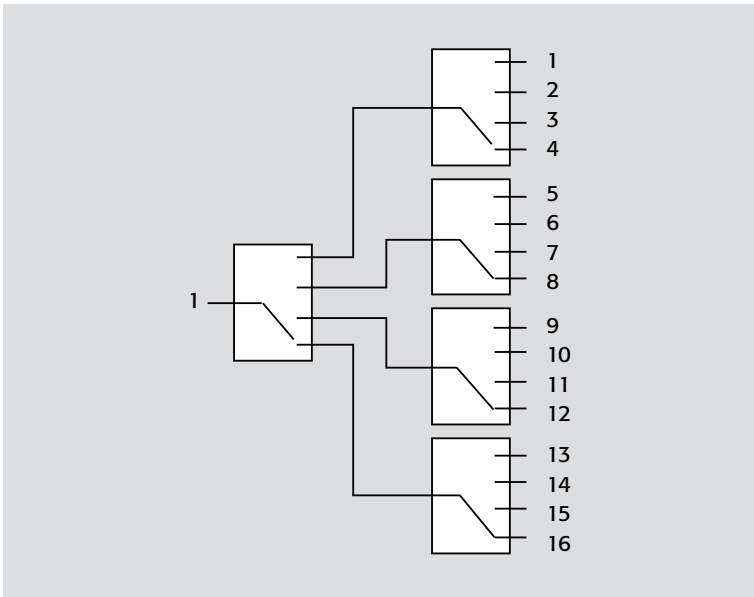
Figure 1-13. Multiplexer (two-tier tree switching)

technique requires more relays for the same size system, but the isolation between a given path and any unused paths may be somewhat better. This will reduce crosstalk and DC leakage. The tree switch configuration is also used at frequencies greater than 10MHz.

The advantages of the tree configuration include the absence of unterminated stubs and the fact that the channels have similar characteristics. However, multiple relays in a given path mean there will be greater losses.

The Model 7016A 50Ω 2GHz Multiplexer Card, the Model 7017 800MHz Multiplexer Card, and the Model 7038 75Ω 2.0GHz Multiplexer Card all employ the tree configuration. The Models 7711 and 7712 for the Models 2700/2701/2750 Integra Multimeter/Data Acquisition/Switch Systems provide dual 1×4 configurations.

Matrix

For a matrix, the number of RF relays and cables required to construct a given switching system (and therefore, its cost) is geometrically related to the number of system inputs and outputs. There are three basic types of matrix switch configurations.

Figures 1-14 and **1-15** are both 4×4 switching matrices. The difference is how many signals can be switched simultaneously. The blocking matrix of **Figure 1-14** allows the connection of a single input to any single output. Therefore, only one signal path is active at any given time.

The non-blocking matrix of **Figure 1-15** allows simultaneous connection of multiple input/output signal paths, up to the full number of matrix inputs, if desired. With its greater number of relays and cables, this configuration is more flexible and more expensive.

Although it is possible to close multiple paths, this is practical only in DC testing, for example, to apply continuous bias voltage to a number of DUTs. Impedance considerations preclude closing multiple paths in RF and microwave testing.

The full or partial access matrix, also referred to as the full or partial fan-out matrix (**Figure 1-16**), allows simultaneous connection of an input to multiple outputs. This type of matrix requires a power divider at each input and a multi-position switch at the outputs.

The advantages of these configurations include the absence of unterminated stubs, access to all channels, and similar path characteristics. Disadvantages include the need for extensive cabling and the use of many coaxial relays. The System 41 and System 46 RF/Microwave Switch Systems can be built using any of the matrix switch configurations.
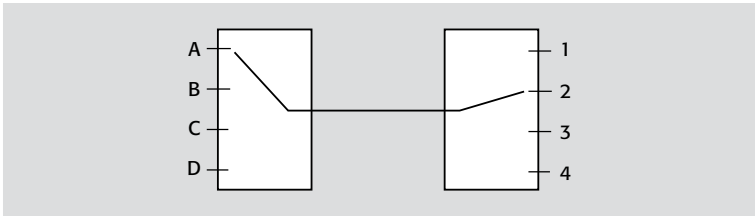
Figure 1-14. Single-channel blocking matrix
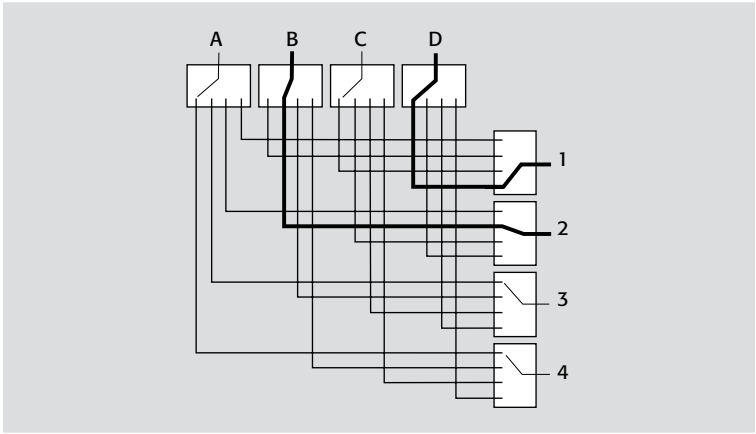
Figure 1-15. Non-blocking matrix
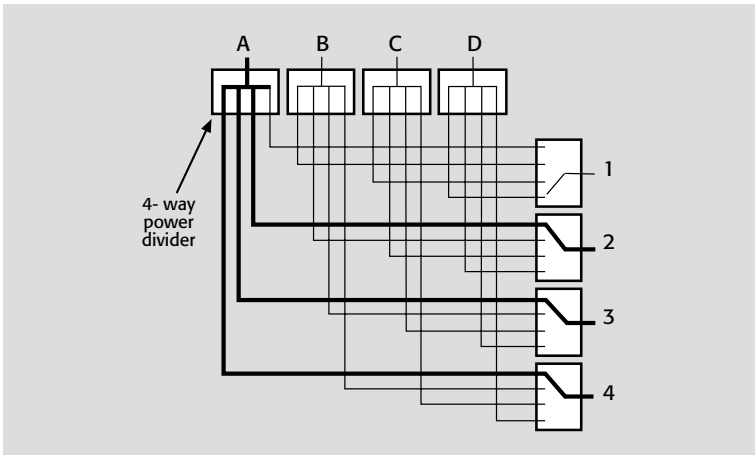
Figure 1-16. Full access matrix

1.5   Switching Hardware Options

Some of the factors to consider when selecting from the variety of commercial switching hardware available include:

- Types of signals to be routed.

- Switching configuration required (for example, multiplex, matrix, etc.).

- Minimum/maximum number of switch points.

- Variety of switching elements available.

- Physical size.

- Cost.

- Expandability.

- Control bus compatibility (for example, GPIB, RS-232).

Some of the switching hardware options include stand-alone scanner mainframes, measurement instruments with integrated scanners, and plug-in data acquisition boards.

Stand-Alone Scanner Mainframes with Switching Cards

Stand-alone scanner mainframes are designed to allow system developers to plug switching cards with relays into slots in the mainframe, which supplies the relay drive current and various controls for the relays. Keithley Models 7001, 7002, 7002-HD, 707A, and 708A are examples of stand-alone mainframes.

This switching hardware option is the most flexible, because of the variety of compatible cards designed for switching various signal types (for example, high voltage, low current). These cards also make it easier to design a system that combines various switching configurations, such as matrix, cascade, tree, etc.

These systems can be expanded easily by adding more cards and/or mainframes and are GPIB programmable.

Instruments with Integrated Switching Capability

A measurement instrument with integrated switching (sometimes referred to as a data acquisition system) provides the convenience of using a single instrument rather than multiple units. With only one instrument involved, the hardware takes up less rack space, is usually more cost-effective, and programming and triggering are less complicated. However, instruments like this may not offer as many switching card options for various signal types, nor as many switch config-

urations, as those offered by stand-alone mainframes. These instruments usually have a wider measurement range with higher resolution and better accuracy than plug-in data acquisition boards. Keithley's Model 2700/2701/2750 Integra Multimeter/Data Acquisition/Switch Systems, the Model 2000/2000-SCAN Scanning Multimeter, and the Model 6517A Electrometer with the Model 6521 Low Current Scanner Card are all examples of this type of instrument.

Plug-In Data Acquisition Boards

Plug-in data acquisition boards are connected to and controlled by a computer, rather than a separate mainframe. PC plug-in cards are a good choice if the application's accuracy and resolution requirements are lower (<16-bit), if the required sampling rate is high (1kHz and above), or if a card-based form factor is preferable for the overall system design. This type of data acquisition system is software dependent, and the number of channels is limited by the space available in the computer. Some systems have external expansion slots to accommodate more data acquisition boards.

With this approach, the engineer will be designing the entire measurement system. This can be a complex process that includes choosing appropriate signal conditioners, isolation circuitry, filtering, scaling, formatting, etc.

SECTION 2

Switching Components

2.1   Switching Elements

A switching element implements the switching function defined by the switch configuration. For use in a switching system, the element must be electrically controllable, and should approximate an ideal switch. (See Section 1 for discussion of an ideal switch and switch configurations.) These two criteria remove many types of switching elements from consideration, even some electrically controllable switches.

For example, a transistor is a controllable switch, but it is directional between the collector and emitter, and it has interactive control between the base and emitter. Both of these considerations make the transistor a poor choice for a signal switching element.

Figure 2-1 shows the schematic representations for four major types of electrically controllable switching elements. **Table 2-1** compares the basic parameters of the four types. As can be seen from the table, the relay family of switching elements offers the best overall performance at a reasonable cost.
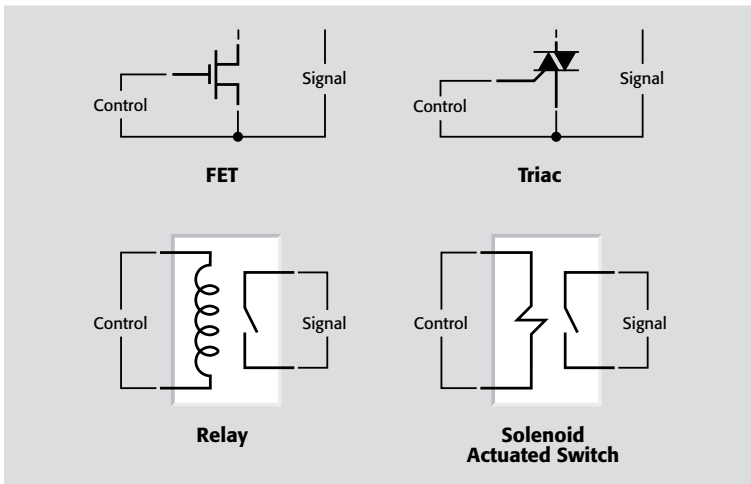
Figure 2-1. Switching elements

Table 2-1. Switching Element Parameters

Element	Life	Size	Cost	Handling	Isolation		Speed*	Form
					Control	In-out		
FET	Long	Small	Low	Poor	Good	Fair	High	A
Triac	Long	Small	Low	Poor	Fair	Poor	Fair	A
Relay	Medium	Medium	Medium	Good	Good	Good	Fair	Many
Solenoid-Actuated Switch	Short	Large	High	Good	Good	Fair	Low	Many

* For a complete off-on-off cycle.

2.2 Types of Relays

There are many types of relays, each designed for a particular purpose. Among the more common types are electromechanical, contactor, dry reed, and solid state. **Table 2-2** compares some key parameters by relay type.

Table 2-2. Relay Comparisons

Relay Type	Isolation	Speed[1]	Power	Life at Rated Load
Electromechanical	$10^7 - 10^{10}\ \Omega$	3 – 100 ms	10 – 100 VA	10^7 cycles
Electromechanical (high frequency)	60 – 130 dB	20 – 100 ms	1 – 120 W	$10^6 - 10^7$ cycles (no load)
Contactor	$10^6 - 10^9\ \Omega$	100 – 250 ms	100 – 4k VA	10^5 cycles
Dry Reed	$10^9 - 10^{14}\ \Omega$	1 – 10 ms	10 – 50 VA	10^7 cycles
Solid State	$10^6 - 10^9\ \Omega$	100 μs – 2 ms	1 – 10 VA	$10^{10} - 10^{15}$ cycles

Notes

1. For a complete off-on-off cycle.

2.2.1 Electromechanical Relays

Electromechanical relays have a coil of wire with a rod passing through the middle (forming an electromagnet), an armature mechanism, and one or more sets of contacts. When the coil is energized, the electromagnet attracts one end of the armature mechanism, which in turn moves the contacts. **Figure 2-2** shows a typical electromechanical relay with the main operating elements labeled and a scheme for actuating the armature.

The coil must generate a strong field to actuate the relay completely. Several parameters contribute to the determination of the force necessary to actuate the relay, among them:
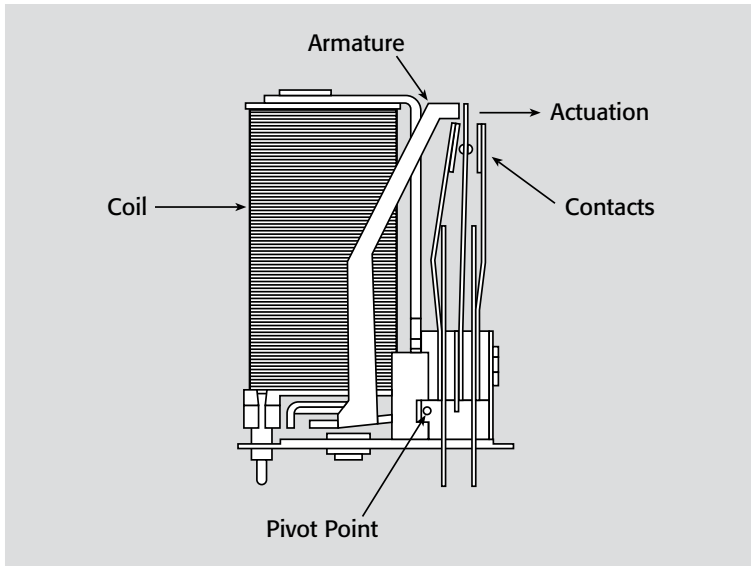
Figure 2-2. Electromechanical relay (armature)

- Spacing of the contacts.

- Spring constant of the material on which the contacts are mounted.

- Mass of the armature mechanism.

(More information on coil design can be found in the *Engineers' Relay Handbook*, 5th edition, National Association of Relay Manufacturers, 1996.)

Electromechanical relays are available in configurations ranging from 1 Form A or B to 12 or more Form C. This type of relay can be operated by AC or DC signals and can switch currents up to 15 amperes, as well as relatively low level voltage and current signals.

Electromechanical relays are available in non-latching and latching types. Non-latching relays return to a known state when power is removed or lost. Latching relays, such as those on several Integra Model 770X cards, remain in their last position when relay drive current is removed or lost. Return mechanisms (for non-latching relays) and latching mechanisms can be magnetic or mechanical, such as a spring.

Since latching relays do not require current flow to maintain position, they are used in applications with limited power. Also, the lack of coil heating, which

minimizes contact potential, makes latching relays useful in very low voltage applications.

2.2.2 Electromechanical Relays (high frequency)

Materials and physical configuration of relays determine inherent capacitances among their components. For example, the capacitance between poles degrades AC signal isolation by coupling the signal from pole to pole or relay to relay. These capacitances within relays are a common factor that limit the frequency of switched signals.

Specialized contacts and architecture are used in electromechanical relays to obtain good performance for RF and microwave switching up to 40GHz. A typical configuration is shown in **Figure 2-3**, where the common terminal is between two switched terminals. All signal connections are coaxial to ensure signal integrity. In this case, the connectors are the female SMA type. For more complex switching configurations, the common terminal is surrounded by switched terminals in a radial pattern.
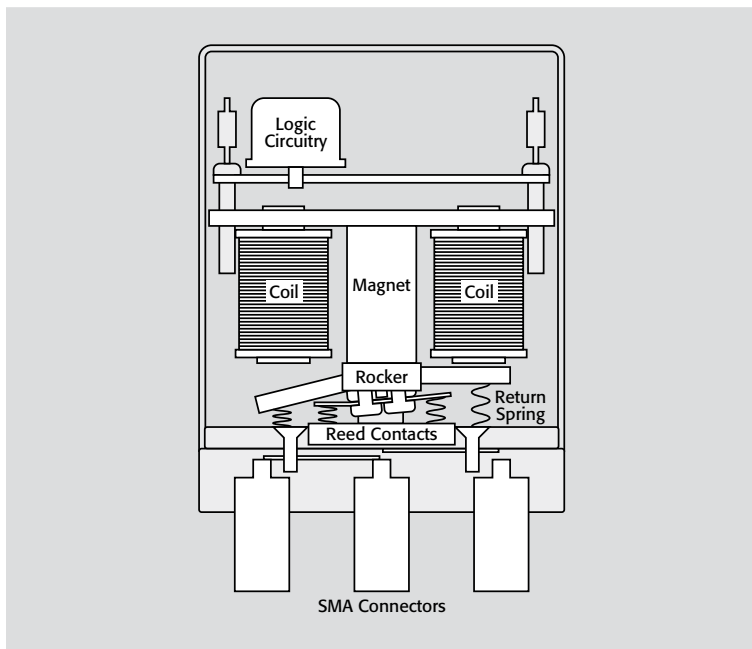
Figure 2-3. Electromechanical relay (high frequency)

2.2.3 Contactors

A contactor is a special type of electromechanical relay, where the contacts are attached to the armature. This type of relay is used to switch currents greater than a few amps and power levels of several hundred to several thousand watts.

The large physical size and limited isolation (due to materials requirements and construction) make this type of relay a poor choice for signal switching.

2.2.4 Dry Reed Relays

Dry reed relays are also operated by energizing a coil, but in this type of relay, the coil is wound around the switch so that the induced magnetic field closes the switch. **Figure 2-4** shows a simplified representation of a typical reed relay.

A. Side view

Contacts   Coil

B. Side (cutaway) view showing lines of electromagnetic force

Force   B Field

Force
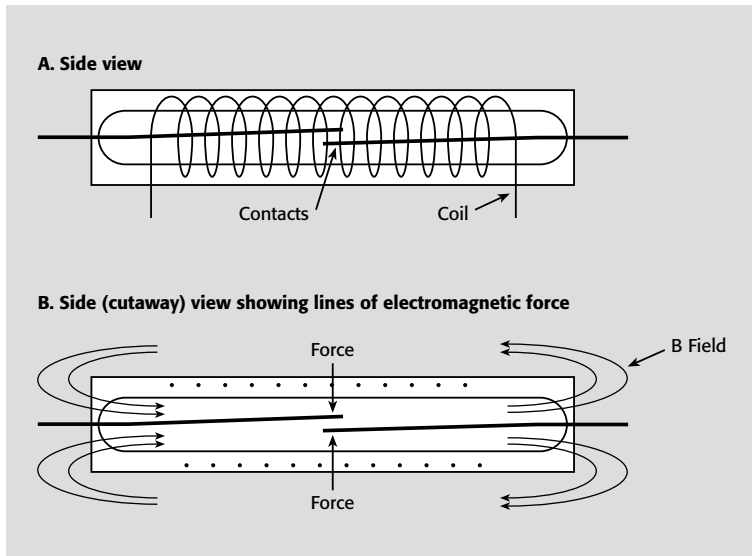
Figure 2-4. Reed relay

The switch is made from two thin, flat strips of ferromagnetic material called reeds, with contacts on the overlapping ends. Leads are connected to the outside ends of the reeds and the entire assembly is sealed in a hermetic glass tube. The tube holds the leads in place (with a small gap between the contacts for normally open switches). See **Figure 2-5**.

Normally closed switches, less common than normally open, are made in one of two ways. The first method is to make the switch so that the contacts are
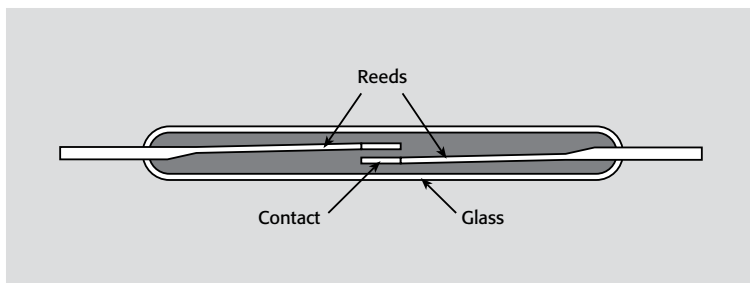
Figure 2-5. Dry reed relay

touching each other. The second method uses a small permanent magnet to hold normally open contacts together. The field from the coil opposes the field of the magnet, allowing the contacts to open.

In order to reduce the oxidation of contacts greatly (or eliminate it), the environment inside the glass tube is often pressurized with a gas that contains no oxygen. A good general-purpose gas has about 97% nitrogen and 3% hydrogen. For high voltage switching (above 500V), the glass tube is evacuated. Although more costly, this provides the highest standoff voltage switch.

To lower the characteristic capacitance and leakage currents of reed relays (and, less commonly, electromechanical relays), an electrostatic shield is sometimes added between the switches and the coil. The shield is typically metal foil that is terminated to a pin connected to some low impedance point in the circuit. Common low impedance connection points are signal low and guard.

An electromagnetic shield can also be added around the outside of the coil. This type of shield keeps the field generated by the energized coil from interfering with other components. It also protects the switch so that random state changes do not occur due to external EMI. (Electromagnetic shields are not placed between the coil and switch since they "protect" the switch and prevent operation.) This type of shield is connected in the same way as an electrostatic shield.

The high permeability of the ferromagnetic reeds in a reed relay causes a pronounced skin effect with increasing signal frequency. Skin effect is current conduction along only the outer surface of a conductor at high frequencies. This causes a dramatic increase in resistance and a decrease in inductance. Signal frequencies carried by reed relays are usually limited to 10MHz or less due to this effect.

Isolated contacts and low operating power make reed relays an ideal choice for many signal switching applications.

2.2.5 Solid State Relays

Solid state relays are typically comprised of an opto-isolator input, which activates a solid state switching device such as a triac, SCR, or FET. Although these are the fastest switching elements when actuation times are compared, the release, or turnoff time, is long. AC control is a normal application for triacs and SCRs because the turnoff time is decreased when the device is switched off during a zero-crossing. Also, their isolation is limited by the leakage currents of the semiconductor devices, and they have a high insertion loss for low level signals.

SECTION 3

Specifications and Models

3.1 Physical Implementation

A physical implementation of the switching topologies described in Section 1.4 includes a circuit board (or card) with relays, connections for inputs and outputs, and supporting circuitry. The cards are usually available in the scan, multiplex, matrix, cascade, tree, and isolated (or independent) switching topologies. Switch cards or modules are designed to plug into a mainframe that supplies drive current for the relays and various control signals.

In terms of the time required to complete a system, purchasing the switching instrument is generally more economical than building one out of components. Although one may be limited to certain configurations with an off-the-shelf instrument, system wiring (as opposed to switch design) can begin at once. Combining topologies makes it possible for the final system to meet even complex switching requirements.

Switch card specifications are usually stated with a specific application in mind, such as low current or high voltage switching. The switch card specifications are based on the performance of the complete card, not just that of the switching element (relay).

This section offers an overview of specifications for relays, switch cards, and mainframes. Definitions for many of the terms and specifications discussed are listed in the glossary.

3.2 Relay and Card Specifications

The specifications for a switching system are determined in large part by the specifications of the relays used to make the connections. **Table 3-1** gives typical values for some key relay specifications. Not all of these specifications can be found in the same relay, but, with trade-offs, each can be obtained.

To help clarify the specifications during system design, **Figure 3-1** illustrates some of the specifications for a single-pole relay mounted on a card. The differential isolation resistance specification usually includes the combination of the input and output resistance (R_{in} and R_{out}), as well as the input and output capacitance (C_{in} and C_{out}). The ideal switch is shown in series with the channel resistance (R_c), which includes both the contact resistance of the switch and the conductors of the circuit board. The contact potential (V_{off}) is an offset voltage caused by temperature gradients across the signal path. This voltage adds to the switched voltage. The offset current (I_{off}) is a spurious current generated by the relay, the connector, and the connecting circuit board traces. This current will combine with the unknown current to be switched.

Table 3-1. Relay Specifications

	Relay Type	
	Electromechanical	**Dry Reed**
Maximum voltage	1000 V	1000 V
Maximum carry current	15 A	1 A
Maximum switched current	15 A	500 mA
Maximum power	500 VA	30 VA
Contact potential	<1 µV	<1 µV
Minimum current	1 µA	10 fA
Actuation time	1–100 ms	0.5–10 ms
Release time	1-150ms	0.5-15ms
Contact resistance	0.01–1 Ω	0.1–2 Ω
Coil power	0.3–10 W	0.1–1 W
Insulation resistance	$10^9\Omega$	$10^{14}\Omega$
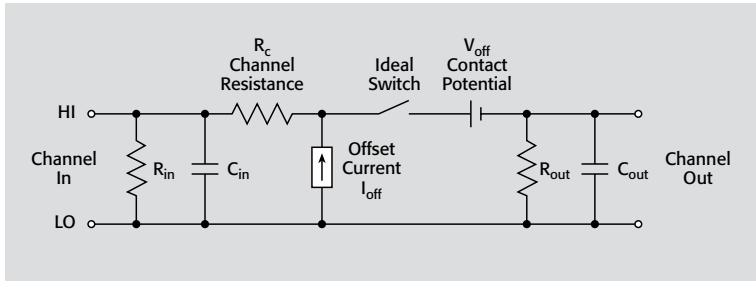
Figure 3-1. Equivalent circuit of an ideal switch mounted on a switch card

This section not only describes the specification, but in some cases, provides information on how to measure a given specification. Information on how the specification may affect system performance may also be provided, as well as compensation techniques, if applicable. Ultimately, this section is a tool to help the user determine which card is best suited for a particular application.

3.2.1 Insulation Resistance

Insulation resistance (IR) is a measure of the resistance between two isolated pins on the relay. These isolated pins include:

• Coil to contact.

• Across an open switch.

• Pole to pole.

Available insulator materials provide a wide range of insulation resistance ($10^5 - 10^{14}\Omega$) in various environments.

Leakage paths are the primary factor in limiting IR. Bulk leakage is through an insulating material, usually after it has absorbed moisture from the environment. Surface leakage is across the surface of the material, usually due to contamination such as flux or salts and other chemicals from fingerprints.

The ambient temperature changes the insulating properties somewhat, but humidity has a much greater effect (several orders of magnitude in many materials). If the insulation or surface contaminants absorb moisture, IR decreases with increasing humidity and with increased exposure time.

The properties of some insulators change with applied voltage, so it is important to evaluate IR at or above the expected operating voltage.

3.2.2 Capacitance

There are inherent capacitances among the components of a relay that are determined by the materials and physical configuration of the relay. Depending on the application, these can alter the performance of the circuit in which the relay is used.

Capacitance from the switch contacts to the coil is typically 0.2–15pF. This capacitance can couple noise or other signals from the contacts to the control lines, and vice versa. Noise can also be coupled to a different switch through its contact-coil capacitance if it is driven by the same coil supply. An electrostatic shield between the switch and the coil can reduce this value by as much as a factor of 100.

There is also a characteristic capacitance across open contacts that is dependent upon the contact area and gap of switch. This capacitance is typically 2pF or less.

The capacitance between poles degrades AC signal isolation by coupling the signal from one pole to another. (The coupling can be on a single relay or from one relay to another.) The value of this capacitance depends on the relay construction and the circuit board material and layout.

3.2.3 Isolation

Isolation is a measure of the leakage resistance between paths on the switch card. The path can be between any terminal and earth ground (common mode) or between any two terminals. For example, this can be the resistance between any two channels (channel to channel) or between the HI and LO inputs of a given

channel (differential). Isolation is specified in terms of resistance and capacitance. The isolation should be as high as possible to avoid errors when switching high impedance circuits.

It is generally unnecessary to verify the isolation capacitance on a switch card, because the capacitance is a mechanical function and should not change over time. In contrast, the isolation resistance does change over time as it is affected by changes in humidity and by contamination due to the environment or handling of the card.

Isolation resistance measurements are usually made by sourcing a voltage, then measuring the resulting current using an electrometer or picoammeter. The isolation resistance is calculated by $R = V/I$. Refer to the instruction manual for the switch card for isolation measurement procedures specific to that card; however, the following paragraphs provide a general description of how to perform isolation measurements.

Channel-to-Channel. This is a measure of the isolation between any two channels on a multiplexer switch card. The measurement is made with one channel open and one channel closed.

Example Measurement of a Two-pole Form A Card (Ch. 1 to Ch. 2)

1. Remove all connections to the card.

2. Connect the HI and LO terminals of Ch. 1 together.

3. Connect the HI and LO terminals of Ch. 2 together.

4. Close Ch. 2.

5. Measure the resistance between Ch. 1 input and Ch. 2 input.

Input Isolation, Differential. This is the isolation between HI and LO on a given channel. This resistance includes the leakage between the poles of a relay, as well as the leakage due to the printed circuit board.

Example Measurement of Two-pole Form A Switch Card (Ch. 1):

1. Remove all connections to the card.

2. Close Ch. 1.

3. Measure resistance between the HI and LO output terminals.

Input Isolation, Common Mode. This is the isolation between the input (HI and LO) of a given channel and the guard or shield. This specification applies only to two-pole cards with a guard or shield and three-pole guarded cards.

Example Measurement (Ch. 1):

1. Remove all connections to the card.

2. Connect the HI and LO terminals of Ch. 1 together.

3. Close Ch. 1.

4. Measure the resistance between either output terminal and the guard or shield terminal.

Path. The path isolation for a matrix card is the impedance from the HI and LO terminals of one path to the HI and LO terminals of any other path. In general, the isolation is measured by applying a voltage (i.e., 100V) between two adjacent paths, then measuring the leakage current. The isolation resistance is then calculated using Ohm's Law (R = V/I).

Example Measurement of a Two-pole Matrix Card (Row 1, Column 1 to Row 2, Column 2)

1. Remove all connections to the card.

2. Connect the HI and LO terminals of Column 1 together.

3. Connect the HI and LO terminals of Column 2 together.

4. Close the crosspoints at Row 1, Column 1 and Row 2, Column 2.

5. Measure the resistance between Column 1 and Column 2.

3.2.4 Maximum Signal Levels

"Maximum signal levels" refers to the highest levels of voltage, current, and power that can be switched without damaging the switch card.

Maximum Voltage

The highest voltage a switch card can withstand reliably is the maximum voltage specification, which is determined primarily by the relay specification. The highest voltage that a relay can switch reliably under given conditions is usually determined by the spacing (gap) between contacts and the dielectric strength of the gas inside the relay.

If the gap is too small, an arc may develop when the contacts open and current continues to flow. Arcing can damage the relay or reduce its life. It is typically present when the switched voltage is above 50V peak in reed and 100V peak in electromechanical relays. An arc due to an AC signal usually quenches itself as soon as the voltage level passes through zero. In addition, the RFI (radio

frequency interference) generated may disrupt high-speed logic circuits in the system.

If switching is done in an inert environment, arcing is greatly reduced. Conversely, if switching is done in a humid or highly oxygenated environment, arcing is increased. Open relays allow ambient air into the switching area, while sealed relays contain a controlled internal environment from the manufacturer. Mechanical types of relays are made as open or sealed units; reed relays, by virtue of their construction, are always sealed.

Outgassing is a problem sometimes seen in sealed electromechanical relays. The arcing combines the internal gas and the vapor of the materials from which the relay is constructed, especially plastics, to deposit an insulating layer on the contacts. This causes contact resistance failures, which will be discussed later in this section.

Maximum Current

Factors that affect the maximum current through the switch card include the traces on the board, the connectors, and the relays. The specification usually includes both the maximum carry current and the maximum switched current.

Carry current is the maximum current the relay can tolerate once the contacts have been closed. The carry current is limited by the cross-sectional area of the path through the switch contacts. The carry current specification applies only when "cold switching." Cold switching is defined as opening and closing the switch when no current is flowing. Contact life is much longer when cold switching is used.

Switched current is the maximum current that can be handled reliably while opening and closing contacts. Contact material and plating are the primary factors that determine this specification. This specification is used to determine the life of the switch. If the switched current is too high, the resulting temperature increase and contact arcing will degrade the relay and shorten the contact life. In extreme instances, the contacts may weld together. Opening and closing the switch when current is flowing is defined as "hot switching."

When evaluating either maximum voltage or maximum current levels, the power rating of the relay must also be considered if the specified life is to be attained.

Maximum Power

The maximum power level, which is expressed in either watts or VA (volt-amperes), cannot be exceeded without damaging the printed circuit board and relays. The maximum power that a relay can switch is specified to limit temperature rise and

provide reasonable contact life. To prevent damage to the switch card, verify that the product of the maximum current and maximum voltage does not exceed the power rating of the switch card.

3.2.5 Contact and Channel Resistance

The contact resistance is the resistance across a closed pair of contacts on a switch card. For dry switches, the contact resistance is inversely related to the contact area. Electromechanical relays with large contacts have a lower contact resistance than a reed switch with relatively small contacts. The channel resistance includes the resistance of the closed contact, the printed circuit traces, and the output connectors.

Usually, repeated operation of a relay will cause the contact resistance to increase gradually over time. Mercury-filled and mercury-wetted relays are exceptions to this general rule. End-of-life is generally considered to be the time when the total channel resistance exceeds the specifications for the switch card.

Dry switches typically have a life specified to a contact resistance less than 1 or 2Ω. Mercury-wetted switches are usually considered to be at the end of their life when their contact resistance has increased by 2–5%. (Typical initial contact resistance for mercury wetted relays is 5–75mΩ.)

A relay may fail in one of several modes, including mechanical (actuation) failure and contact failure. Mechanical failure can be caused by a coil wire break, a glass seal fracture or reed fatigue in reed switches, or an armature mechanism failure in electromechanical relays.

Contact failure can occur when excessive heat or a high current or voltage pulse causes the contacts to weld together, resulting in short circuits. An open circuit can be caused by oxidation, excessive charring and pitting, or insulating deposits on the contacts.

Given the importance of the actual contact to the life of the relay, much effort has gone into finding and choosing "good" contact materials. Gold, silver, and palladium have traditionally been used for their good electrical conductivity and relatively low susceptibility to oxidation. Increasingly, rhodium and ruthenium are being plated over more traditional contact materials to increase the contact life. Rhodium's structure is cubic, which is more stable than that of earlier contact platings. For even greater stability, the hexagonal structure of ruthenium is used.

The channel resistance may cause a significant voltage drop if the current being switched is high enough. To minimize measurement error due to channel resistance, use a four-wire switching circuit. Refer to Section 5.4.1 for further information on four-wire switching.

Measuring the channel resistance verifies that the relay contacts are closing properly and that the resistance is within specification. The channel resistance is measured with a four-wire ohmmeter. The steps required to measure the channel resistance are usually described in the operating manual for the switch card. However, the following example illustrates the technique for measuring the channel resistance of a two-pole Form A card.

Example Channel Resistance Measurement of a Two-pole Form A 10-Channel Card (see **Figure 3-2***):*

1. Remove all connections to the card.

2. Connect all input terminals of the card (or bank) together to form one terminal, as shown in **Figure 3-2**.

3. Connect the HI output terminal of the switch card to the LO Source and LO Sense terminals of a four-wire ohmmeter.

4. Connect Ch. 1 HI to the HI Sense terminal, and connect Ch. 10 LO to the HI Sense terminal, as shown in **Figure 3-2**. This will allow the HI channel resistance of each channel to be measured.

5. Install the switch card into the scanner mainframe.

6. Close Ch. 1 and measure the resistance. Verify that the HI channel resistance is within the published specification.

7. Open Ch. 1 and then close Ch. 2. Verify that Ch. 2 is within specification.

8. Repeat this procedure for all channels.

9. Disconnect the LO Source and LO Sense leads from the HI Output terminal and connect them to the LO Output terminal of the switch card. This will allow the LO channel resistance to be measured.

10. Close Ch. 1 and measure the resistance. Verify that the LO channel resistance is within the published specification.

11. Open Ch. 1 and then close Ch. 2. Verify that Ch. 2 is within specification.

12. Repeat this procedure to measure the LO channel resistance for each channel.
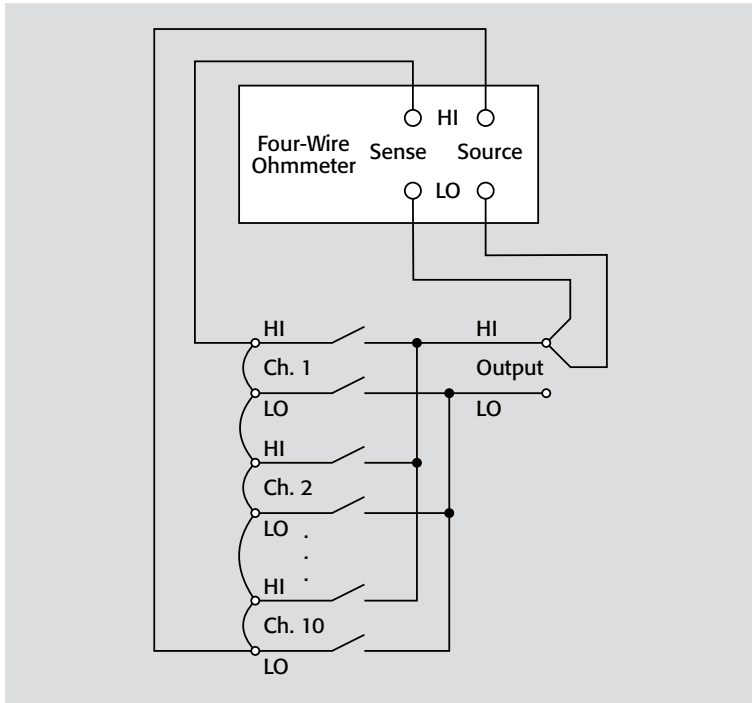
Figure 3-2. Measuring channel resistance of two-pole Form A 10-channel card

3.2.6 Contact Potential

Contact potential is an offset voltage that is primarily due to the thermoelectric EMFs generated by the relay contacts but will also include any other spurious voltages introduced by connectors and junctions in the signal path. This offset voltage adds directly to the signal being switched, which means that the contact potential can cause significant errors when switching very low voltages. Depending on the relay(s) in the signal path, this error may range from less than one microvolt to tens of microvolts. If the error is significant with respect to the source or measure value, the contact potential can be measured and compensated for to preserve system accuracy. Refer to Keithley's *Low Level Measurements Handbook* for a discussion of thermoelectric EMFs.

In some switch cards with two-pole reed relays, the offset voltage will be less when the poles are used as a pair because the offset voltages tend to cancel each other. Other cards, such as the Model 7700 20-Channel Differential Multiplexer

Module, use latching relays, and the offset voltage is the same whether the poles are used as a single pole or as a pair.

To compensate for the contact potential when switching low voltages, place a clean copper short on an unused channel. Close the channel and measure the voltage with a sensitive voltmeter. Open the short-circuited channel and subtract this measured value from readings taken through other channels.

Contact potential is affected by changes in ambient temperature as well as by the presence of temperature gradients across a switch card. Such effects can be reduced by thoughtful placement of a switch card within a switch mainframe and of a switch system within an equipment rack. For example, if it is possible to install a switch card being used for low voltage measurements in a slot away from the mainframe's power supply, then it is a good idea to do so. Once the relay is closed, the contact potential may still change with time due to heat generated in the relay coil. Therefore, the offset voltage should be measured periodically for the most effective offset correction. A latching relay will minimize this effect because the coil will dissipate power for only an instant.

Making low resistance measurements usually requires sourcing a test current and measuring a low voltage. When making these measurements through a switch, errors due to contact potential can be minimized by using offset compensation, which involves taking two voltage measurements with two different known currents. The resistance is calculated by dividing the difference between the voltage measurements by the difference between the two source currents. The offset error will be eliminated from the measurement. Refer to Section 5.4.1 for more information on offset compensation.

To verify a switch card's specifications, the contact potential can be measured with a sensitive voltmeter. Refer to the switch card's operating manual for the specific procedures for that card.

Example Contact Potential Measurement of a Two-pole Form A Card:

1. Using clean copper wire, place a short between the HI and LO terminal of each channel.

2. Connect a warmed-up sensitive voltmeter or nanovoltmeter to a low voltage calibrator and output zero volts. Zero the meter. Then connect the voltmeter to the HI and LO output terminals of the switch card.

3. Install the switch card into the mainframe and allow the instruments to warm up.

4. Select the lowest range of the voltmeter.

5. Close Ch. 1.

6. Allow the reading to settle and verify that the contact potential of the channel is within the specification.

7. Open Ch. 1 and repeat the procedure for all other channels.

3.2.7 Offset Current

Offset current is the current generated by the circuit as measured at the output when no signal is applied. To achieve accurate results, the offset current specification must be smaller than the signal current that is being switched. Given that the offset current may be hundreds of picoamps or less, an electrometer or picoammeter is required to measure it.

Example measurement (Ch. 1):

1. Disconnect all leads from the inputs of the switch card.

2. Close Ch. 1.

3. Connect an electrometer to the switch card output and measure the current. The current should be measured after a sufficient settling time to allow the switching transients to decay and the current to stabilize.

4. Open Ch. 1 and repeat the procedure for all other channels.

3.2.8 Operating Speed

Operating speed of a relay is the rate at which the contacts may be cycled for reliable operation. It is limited by the actuation and release times. Actuation time is measured from when power is applied to the coil until the contacts have settled. This is shown in **Figure 3-3**. The bounce time must be included for accurate measurements.

Release time is the opposite of actuation time. It is measured from the time power is removed from the coil until the contacts have settled, again including bounce.

A repetition rate, or operating frequency, lower than that allowed by the switching times is often specified for a relay. This is to limit temperature rise and allow for contact settling. Of these two, temperature rise is more critical. When a relay is used near its power or voltage rating, the duty cycle must be adjusted to allow for cooling time. A lower operating frequency or altered duty cycle accomplishes this.
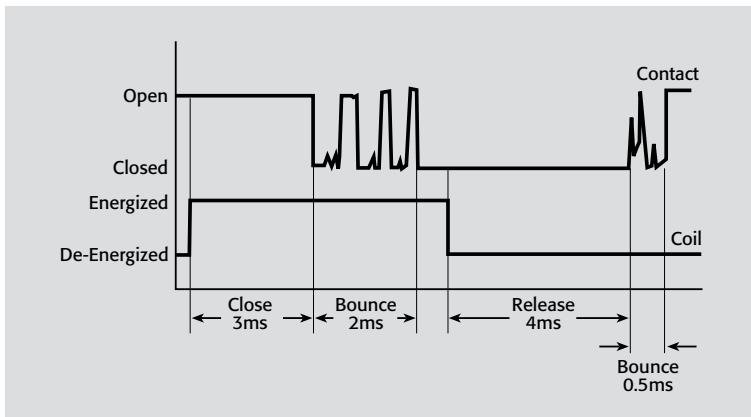
Figure 3-3. Dry reed relay operating speed

It is important to recognize that switch settling and signal settling are not the same thing. After a switch is fully closed and settled, it is often necessary to wait longer for the signal to settle out (reach equilibrium) before making a measurement. The signal settling time is affected by the RC time constant of the system. For low current and high resistance measurements, signal settling time can easily be many seconds.

3.2.9 Coil Power

Coil power is the amount of power in watts needed to actuate the relay. A reed switch or the armature of an electromechanical relay requires a set amp-turns product to actuate the relay. Many turns of fine wire are used to keep the necessary current, and therefore power, to a minimum. Coil resistance is determined by the cross-sectional area and length of the wire used in winding the coil.

The resistance of the coil and the amp-turns requirement also determine the pull-in, hold, and drop-out voltages. These are shown for a typical 5V DC relay in **Figure 3-4**. More power is needed to actuate a relay than to maintain a given state. Once the switch is closed, the magnetic path has a lower reluctance. A lower reluctance means a weaker field can hold the switch closed.

As with any wire, the coil's resistance changes with temperature. This affects the pull-in voltage, as shown in **Figure 3-5**.

A relay coil also has inductance since it is a coil of wire. As an inductor, the current in the coil cannot be changed instantaneously, since $V = L \, (di/dt)$, without generating an excessive voltage spike. A diode is sometimes connected across the
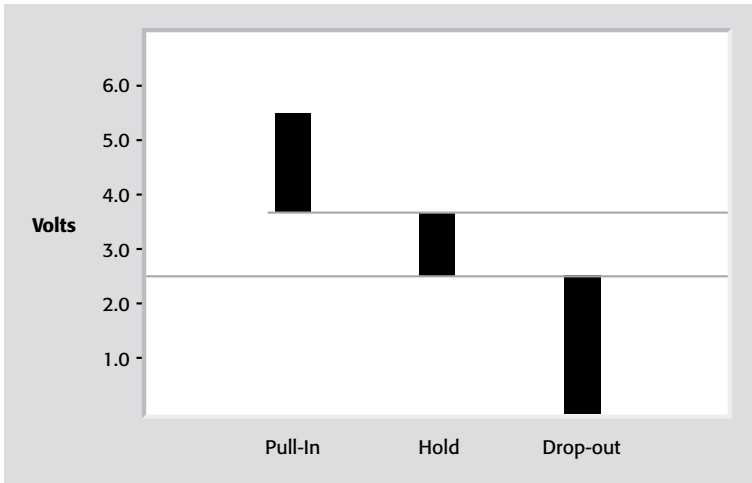
Figure 3-4. Coil voltage levels
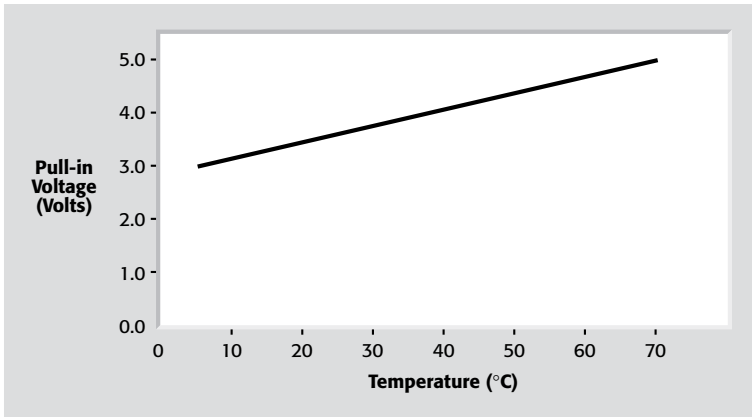
Figure 3-5. Pull-in vs. temperature

coil with the cathode at the positive voltage end of the coil. The suppression or "back" diode will conduct the coil current when the relay drive is removed. This is shown in **Figure 3-6**.

It is useful to understand the meaning and characteristics of coil power, but one generally does not have to consider this specification when selecting a switch card. Switch card specifications typically specify relay drive current rather than coil power. This value can be used with the drive current capacity specification
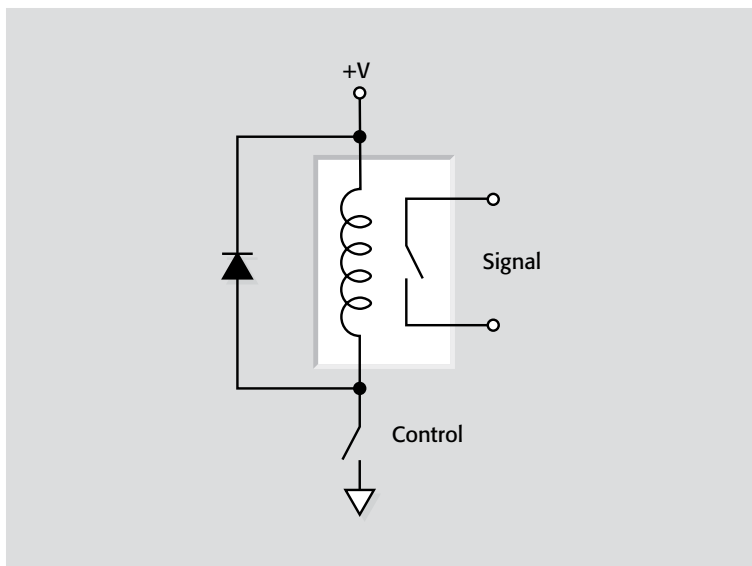
Figure 3-6. Suppression diode

for a switch mainframe to determine how many relays the mainframe can close at one time.

3.2.10 Crosstalk

Crosstalk is a measure of the high frequency signal leakage from one channel to another. It is the result of stray capacitance, mutual inductance, and leakage resistance between channels and is generally given in decibels at a specific frequency.

Figure 3-7 shows an example of crosstalk. In this example, a 10VAC signal source (V_1) is connected to a load resistor (R) through Ch. 1 of the switch card. An AC voltmeter (V_2) is connected through Ch. 2 to a second signal source.

The crosstalk caused by impedance (Z) between Ch. 1 and Ch. 2 is specified in decibels as:

crosstalk (dB) = 20 log $\dfrac{V_2}{V_1}$

This equation can also be expressed in terms of RF power:
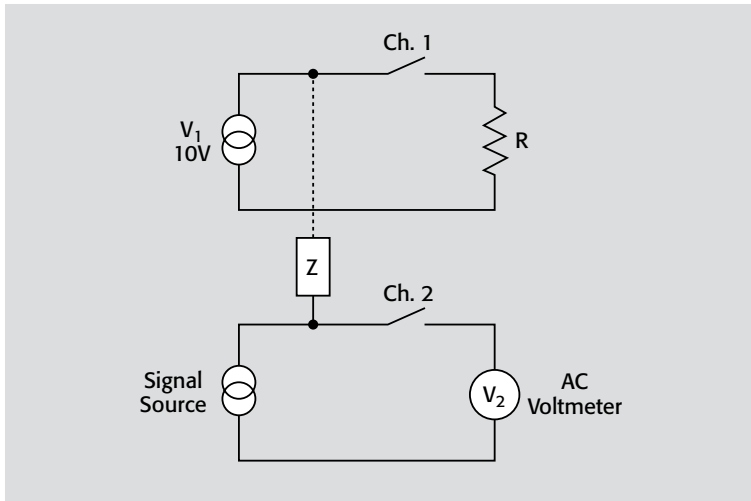
Figure 3-7. Crosstalk example

RF power (dB) $= 20 \log \dfrac{P_2}{P_1}$

To find the maximum signal on Ch. 2 due to the signal on Ch. 1, the equation is solved for V_2:

$V_2 = V_1 \, [10^{(\text{crosstalk (dB)}/20)}]$

For example, if the channel isolation or crosstalk specification is -60dB, the 10V signal on Ch. 1 will cause the following voltage to appear at V_2 with the signal source set to zero volts:

$V_2 = V_1 \, [10^{(-60/20)}]$

$V_2 = 10\text{V} \, (10^{-3})$

$V_2 = 10\text{mV}$

If the signal to be measured at Ch. 2 is only a few millivolts, this additional voltage will cause a significant error.

If a switch is to be used for DC or very low frequency AC signals, it might be easier to consider the isolation in terms of a leakage resistance with parallel shunt capacitance. Refer to Section 3.2.3 for more information on isolation.

3.2.11 **Insertion Loss**

Insertion loss is a measure of the decrease in signal magnitude due to the switch in the signal path. Insertion loss is given in dB, often with a 50Ω source and a 50Ω load, and at a specific frequency.

Figure 3-8 is a schematic of an RF switch card that connects a voltage source (V_S) with output impedance (Z_S) of 50Ω to a voltmeter with a 50Ω input impedance (Z_L).
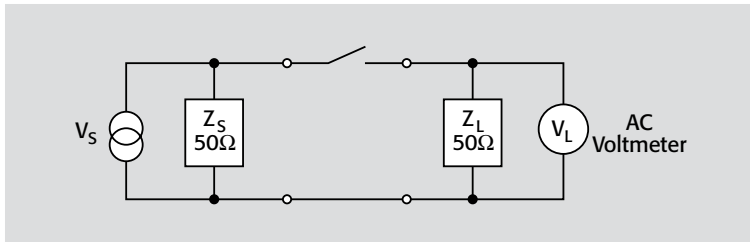
Figure 3-8. Insertion loss example

The insertion loss is calculated as follows:

$$\text{Insertion Loss (dB)} = 20 \log \frac{V_L}{V_S}$$

To determine how the insertion loss can affect the signal, the measured value (V_L) at the voltmeter can be calculated from the insertion loss as follows:

$$V_L = \frac{V_S}{10^{[\text{Loss(dB)}/20]}}$$, where loss is expressed as a positive value.

If V_S is 10V and the insertion loss is <1.0dB, then:

$$V_L > \frac{10V}{10^{(1.0/20)}}$$, or 8.9V.

3.2.12 **VSWR and Return Loss**

The Voltage Standing Wave Ratio (VSWR) of a switch card specifies how well the connectors and switching signal path are matched to the characteristic impedance of the transmission line. More specifically, VSWR is the ratio between the voltage at the maximum point of the standing wave and the voltage at an adjacent minimum of the standing wave. With a VSWR equal to one, the transmission line has no reflected wave present. With a VSWR greater than one, part of the switched signal is reflected back to the source and less than the maximum power

will be transferred to the load. Low VSWR is crucial for switching systems that are designed for signals involving multiple components in series.

The VSWR is also related to the reflection coefficient by:

$$\text{VSWR} = \left| \frac{\rho + 1}{\rho - 1} \right|$$

where ρ = reflection coefficient

The reflection coefficient is the ratio of the reflected wave voltage to the incident wave voltage, and is calculated by:

$$\rho = \frac{Z_L - Z_S}{Z_L + Z_S}$$

where: Z_L = the impedance of the load
Z_S = the impedance of the switch card

To prevent problems, all components in the system should have low VSWR.

VSWR can also be expressed as return loss:

$$\text{Return loss (dB)} = -20 \log \frac{(\text{VSWR} - 1)}{(\text{VSWR} + 1)}$$

For the example shown in **Figure 3-9**, the system has a VSWR of 1.50:1, the return loss is 14dB, and with 50W forward power, reflected power is 2W.
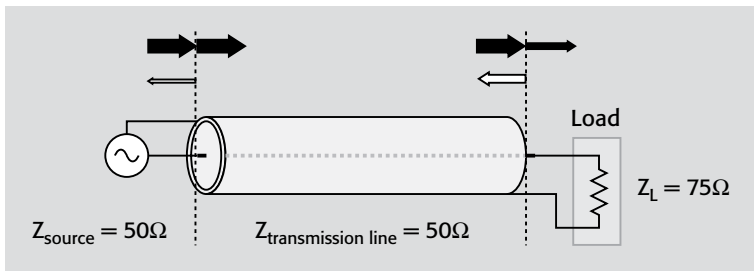
Figure 3-9. Impedance mismatch example

3.2.13 **3dB Bandwidth**

The 3dB bandwidth is the maximum recommended frequency of a sinewave signal through the switch card. This is the frequency at which the signal will be reduced to 0.707 times the mid-band signal level.

This specification is based on a single switch card. If two or more cards are connected together, the 3dB bandwidth will be reduced.

If the switch is to be used for digital signals, the minimum bandwidth can be determined from:

$$\text{Bandwidth (Hz)} = \frac{0.35}{\text{risetime(s)}}$$

3.2.14 Switch Card Topologies

The phrase "switch card topology" refers to the manner in which the individual relays on the switch card are connected together, such as multiplex, matrix, or isolated. Depending on the switch card, the configuration may also specify the number of the poles, the size of the matrix, the number of channels, or the number of banks. Section 1.4 provides a discussion of switching topologies.

"Switch (or contact or crosspoint) configuration" specifies the form and number of poles of the relays used on the switch card, as well as any guard or shield connections. Section 1.3 offers further information on switch configurations.

3.3 Relay and Card Equivalent Circuit Models

This paragraph contains models of relays and circuits that implement the previously described switching topologies.

These models surround a perfect or ideal switch by effects that make it less than ideal. These effects are modeled as components or sources. In reality, each of these is a distributed effect. The simplified circuit models are still reasonably accurate.

The models assume all transient conditions (such as contact bounce) have settled out and a steady state condition exists. Most of the models also assume DC or low frequency (<1MHz) signals. Therefore, effects such as line inductance and transmission line characteristic impedance, which become significant when switching RF signals, are ignored. The typical values shown are for a good quality dry reed relay.

3.3.1 Relay Model

Figure 3-10 shows a circuit model of a simple relay switch. An ideal switch is in series with contact resistance, which includes contact and lead resistance. A small thermally induced contact potential ($V_{CONTACT}$) is also in series with the contact.

Typical Values:

$R_{Coil\text{-}Contact}$:	$10^{10}\Omega$
$C_{Coil\text{-}Contact}$:	$1pF$
$R_{Contact}$:	1Ω
$C_{Contact}$:	$2pF$
$R_{Contact\ Leakage}$:	$10^{9}\Omega$
$V_{Contact}$:	$30\mu V$
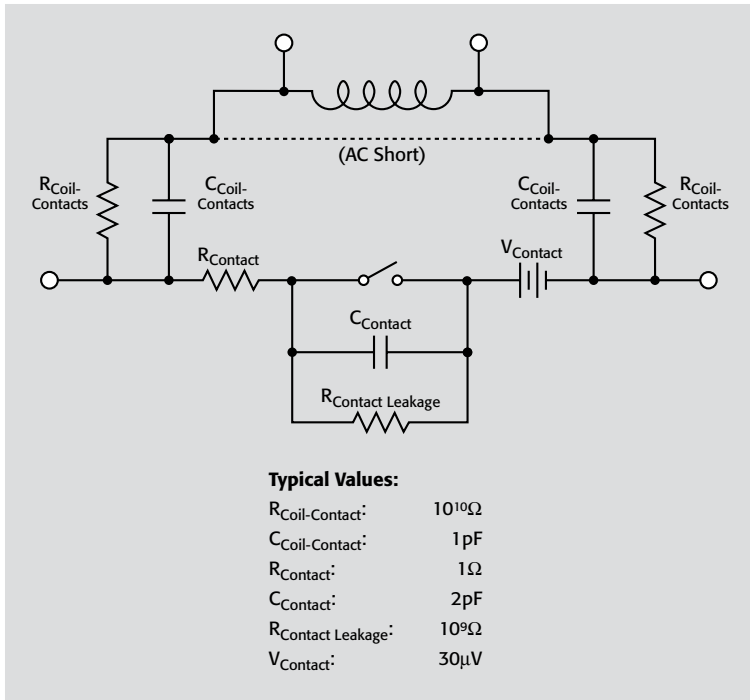
Figure 3-10. Switch model relay

Their effect is only seen when the contact is closed. Contact resistance causes a voltage drop when current flows through the switch and the contact potential adds (or subtracts) from any voltages being switched by this device.

In parallel with the ideal switch is the contact leakage resistance and capacitance. When the contact is closed, these are shorted, so their effect is only seen when the switch is open. The next result of these leakage elements is that a small current flows even when the switch is open. This current increases at higher frequencies.

Also shown in the model are the coil-to-contact resistance and capacitance. These items also let small currents flow when the coil is energized or when there is a voltage difference between the coil and the contact. The dotted line connecting the tops of the two capacitors represents the low coil impedance to AC signals. It is as if the capacitors are connected.
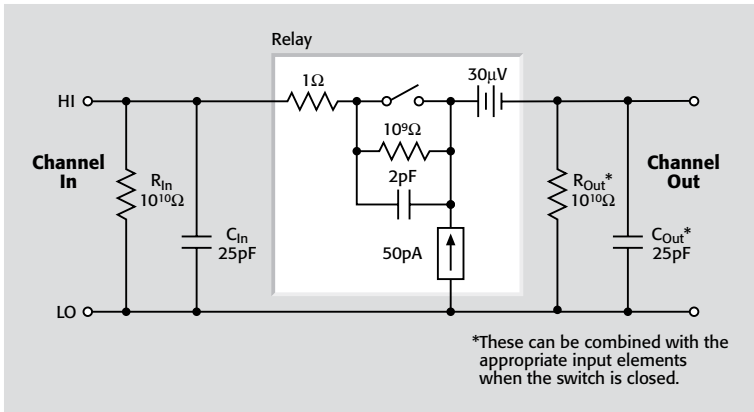
Figure 3-11. One-channel one-pole switch

3.3.2 Equivalent Circuit Card Models of Typical Switch Card Configurations

One Channel One-Pole Switch

As soon as a one-pole relay is placed on a card, a number of new items appear in the model. In addition to the relay, there are connections and wiring for the LO and HI terminals. These are usually implemented as traces on a printed circuit board. As with any wiring arrangement, there are leakage resistances and stray capacitances between the conductors. R_{IN}, R_{OUT}, C_{IN} and C_{OUT} represent these items in the model (**Figure 3-11**). These elements will allow leakage currents to flow or cause shunt loading errors in high impedance circuits.

Three simplifications were made to the model. First, all the contact-to-coil elements were combined into a current source from the contact to LO. This is reasonable, since the contact-coil impedance is in series with the control circuit to LO isolation impedance (i.e., the power supply). While the typical value of the current source is shown as 50pA DC, this can vary by several orders of magnitude. Its polarity can also be positive or negative. This current will cause errors in low current measuring or in high impedance circuits. This current also has an AC component. It can cause noise in the measurement system. A system with good normal-mode noise rejection can usually remove this noise from the measurement.

The second simplification was to combine the trace resistances with the contact resistor. A typical value of one or two ohms is still reasonable.
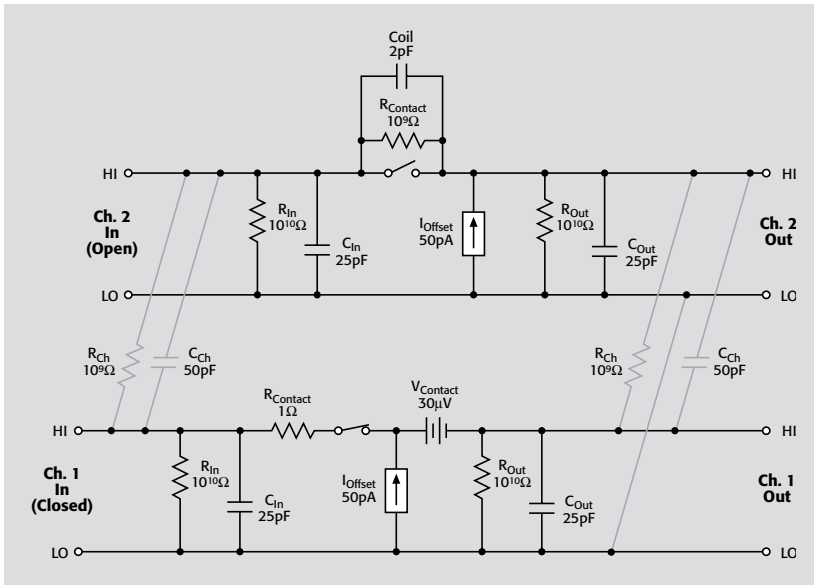
Figure 3-12. Two-channel one-pole switch

Thirdly, LO is assumed to have zero impedance through the card. This is valid only if input and output LO are connected at the same point. In reality, this value should be a few tenths of an ohm to a few ohms due to trace resistance. This resistance is present in all connecting lines.

Two-Channel One-Pole Switch

Most cards contain a number of switches. Again, due to the wiring arrangements, there are additional resistances and capacitances in the model. They allow signals (voltage or current) from one channel to enter another channel. In **Figure 3-12**, these are shown as R_{CH} (resistance, channel-to-channel) and C_{CH} (capacitance, channel-to-channel). These elements, like other elements in the model, are distributed across the entire circuit. They can usually be grouped together in one place, but this depends on the complete system model. For example, if a high gain amplifier is connected to the output, the output isolation elements would be modeled there. In the following models, input will be used for simplicity.

In commercially available switching hardware, R_{CH} and C_{CH} are referred to as channel isolation (given in resistance and capacitance) or as channel-to-channel crosstalk (given in dB rejection). The actual values of R_{CH} and C_{CH} can vary greatly depending on channel location. The channels closest to each other show the lowest isolation.

Figure 3-13. Two-channel two-pole switch

Another simplification was applied to this model. Only the applicable elements of a closed or open relay are shown. This was done to make this and all following models more readable. Also, note that in most one-pole cards, all LO terminals are common. LO is usually connected to the card shield.

Two-Channel Two-Pole Switch

Floating measurements, where a signal is on the HI and LO leads, require a two-pole switch. The switch in the LO lead is always in the same state (open or closed) as the HI lead.

Because signals can be on both connections, they must be isolated from system common as well as each other. In the ideal case, they should be completely isolated from everything else. In reality, there are leakage resistances and stray capacitances from and to everything. The model (**Figure 3-13**) is an attempt to show a reasonable representation of these elements.

The most obvious new elements are the switch in the LO lead, R_{CM} (resistance, common mode) and C_{CM} (capacitance, common mode). R_{CM} and C_{CM} cause the same type of leakage and shunt errors in low current and high impedance circuits as seen earlier.

The two-pole switch has a slightly different input isolation specification than a one-pole switch. The isolation from input HI to input LO is usually referred to as differential input isolation. This is the same input isolation that was shown in previous models. The common-mode isolation is from input HI and/or input LO to system common.

In the model, R_{CM} and C_{CM} from HI to common are not shown. This was done to prevent cluttering the drawing. Also, these values are usually specified with input HI and LO connected together. It is therefore not unreasonable to model them this way.

Two-Channel Two-Pole Multiplexer

As was discussed earlier in this section, a multiplexer is one of the common topologies used in switching systems. Many channels are tied together to a single output connector (N:1). Since large portions of the circuit are tied together, many elements of the model can also be combined. **Figure 3-14** shows all the elements of the output side combined with the input elements of the closed channel. They are shown as a single resistor, capacitor, and current source. The typical values shown are derived by adding the separate parallel elements. The actual values depend on the number of channels and the way the connections are made.

To other
channels

* All output elements
combined. N is
number of channels.

† May or may not be
available as a user
connection.

All $R_{Ch} = 10^9\Omega$
All $C_{Ch} = 50pF$

HI

Ch. 1
Out

LO

Common †

$C_{Contact}$
2pF

$10^9\Omega$

$R_{Contact}$ Lkg.

$10^9\Omega$

2pF

C_{In}
25pF

C_{cm}
150pF

R_{In}
$10^{10}\Omega$

R_{cm}
$10^9\Omega$

C_{Ch}

C_{Ch}

$V_{Contact}$
30µV

I_{Offset}*
50pA × N

$V_{Contact}$
30µV

$R_{Contact}$
1Ω

C_{Diff}*
25pF × (N+1)

$R_{Contact}$
1Ω

C_{cm}
150pF

HI

LO

Ch. 2 In
(Open)

R_{Ch}

R_{Ch}

R_{Ch}

R_{Diff}*
$\dfrac{10^{10}\Omega}{N+1}$

R_{cm}
$10^9\Omega$

HI

LO

Ch. 1 In
(Closed)

Common †

Figure 3-14. Two-channel two-pole multiplexer

The main point of this model is to show how quickly specifications can degrade. As more channels are connected together, leakage paths, stray capacitances, and error currents all increase.

One-Channel Three-Pole Guarded Switch

The three-pole switch was originally used to switch a voltmeter guard along with the signal lines. The HI and LO terminals connect the voltmeter to the DUT being measured. The guard terminal from the voltmeter attaches to the LO terminal of the DUT. This shunts common-mode (LO to ground) signals away from the HI and LO signal lines. The common-mode signals could cause errors or noise if they enter the measurement circuit. Switching the guard was necessary for floating measurements since guard is at the same potential as the DUT LO terminal.

Figure 3-15 shows a model of a three-pole guarded switch. As in the guarded voltmeter, the guard surrounds the HI and LO signal lines and switches. This forms a shield around them. All leakage elements (R_{CM}, C_{CM}) are connected to the guard instead of directly to ground. The offset currents are much lower since the contacts are shielded from the coil.

The guard is usually implemented with shielded relays and traces on a printed circuit board. The guard trace is routed around the signal traces. The hardest part of designing a properly guarded switch is to fit all the traces on the board and maintain proper voltage spacing. The more complete the guarding, the better the performance.

Three-Pole Multiplexer (Driven Guard)

There are many applications where input and channel-to-channel isolation must be as high as possible. This is critical in systems designed to measure voltages from high impedance sources or high value resistances. One way to improve isolation is through special (i.e., expensive) relays. Very high quality insulators and point-to-point wiring on insulated standoffs are also used. Even if all this is done to the switch card, external connectors and cables can still degrade performance.

An alternate approach is to use a driven guard. The three-pole switch from the last model (**Figure 3-15**) can be used in this application. All isolation elements (R_{CM}, C_{CM}, R_{CH}, C_{CH}) connect to GUARD instead of system common or other signal lines. LO is not connected to isolate HI completely. Now, a low impedance voltage, equal to the voltage on HI, can be placed on GUARD. For example, if HI has 10 volts on it, GUARD is also forced to 10 volts. The guard voltage can be provided by a measuring instrument (electrometer) or a source designed to provide a driven guard signal.
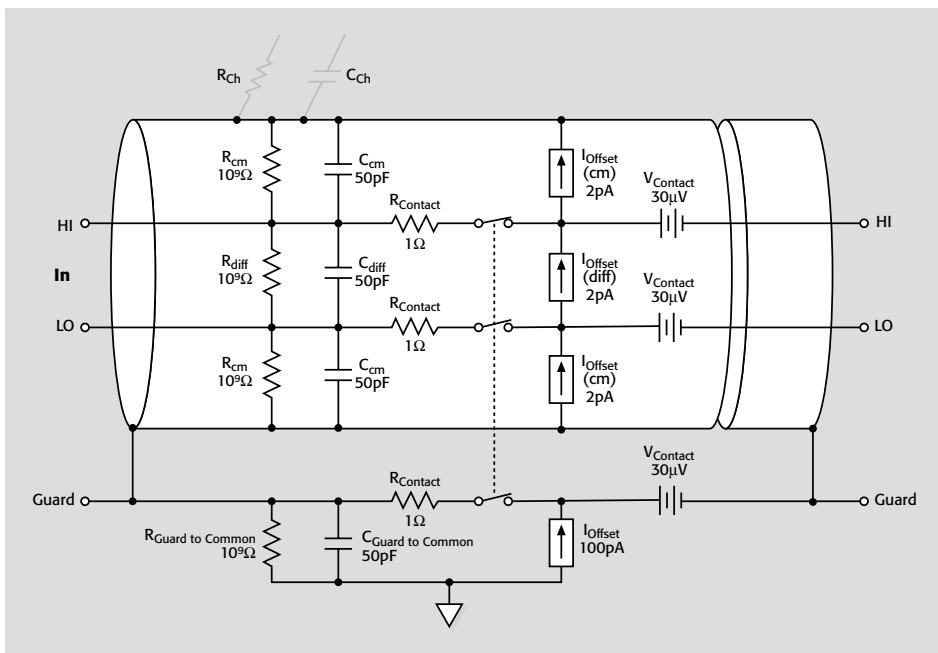
Figure 3-15. One-channel three-pole guarded switch

Now R_{CM} and C_{CM} of channel 1 HI have no voltage across them. No leakage current flows through R_{CM} and C_{CM} does not charge. Therefore, their effect is significantly reduced. Because GUARD is driven from a low impedance source, the leakage from GUARD to system common is not a problem.

The guard line is normally routed through the whole system to reduce leakage and capacitance effects in cables and connectors too. The problem of I_{OFFSET}, however, remains. Proper selection and shielding of the relays has reduced this to acceptable levels. While this method allows some unguarded stray elements to remain, it provides very good performance at an acceptable cost.

When using driven guard, the capacitance on the guard relay (C_{GUARD} to common) can cause a problem. This capacitance, when combined with cable capacitance, can become a large value. This can cause the guard voltage to be time delayed or phase shifted from the signal on HI. Leakage current will now increase. In extreme cases, the source of the guard voltage can become unstable and start to oscillate. This will inject noise into the system. This effect is especially critical for AC or transient signals. Always verify the specifications of the instrument driving the guard to prevent this problem.
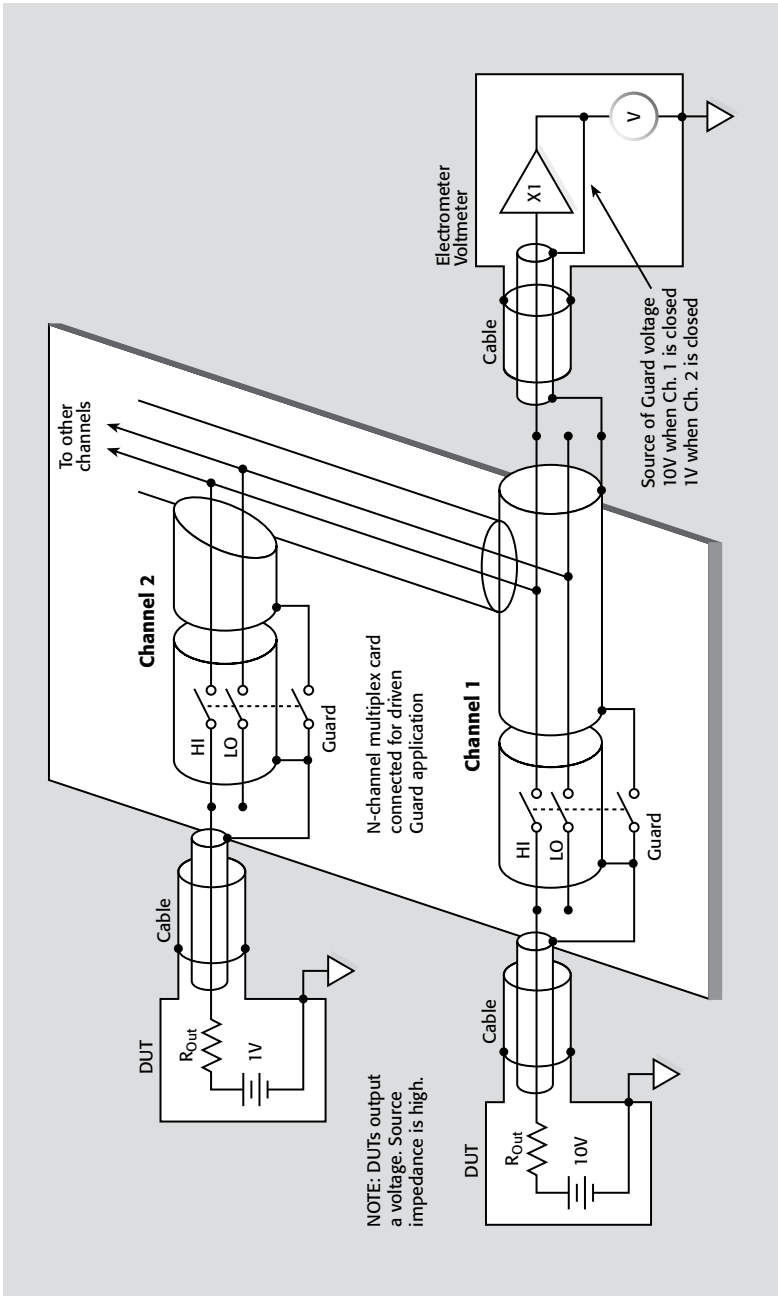
Figure 3-16. Three-pole multiplexer (driven guard)
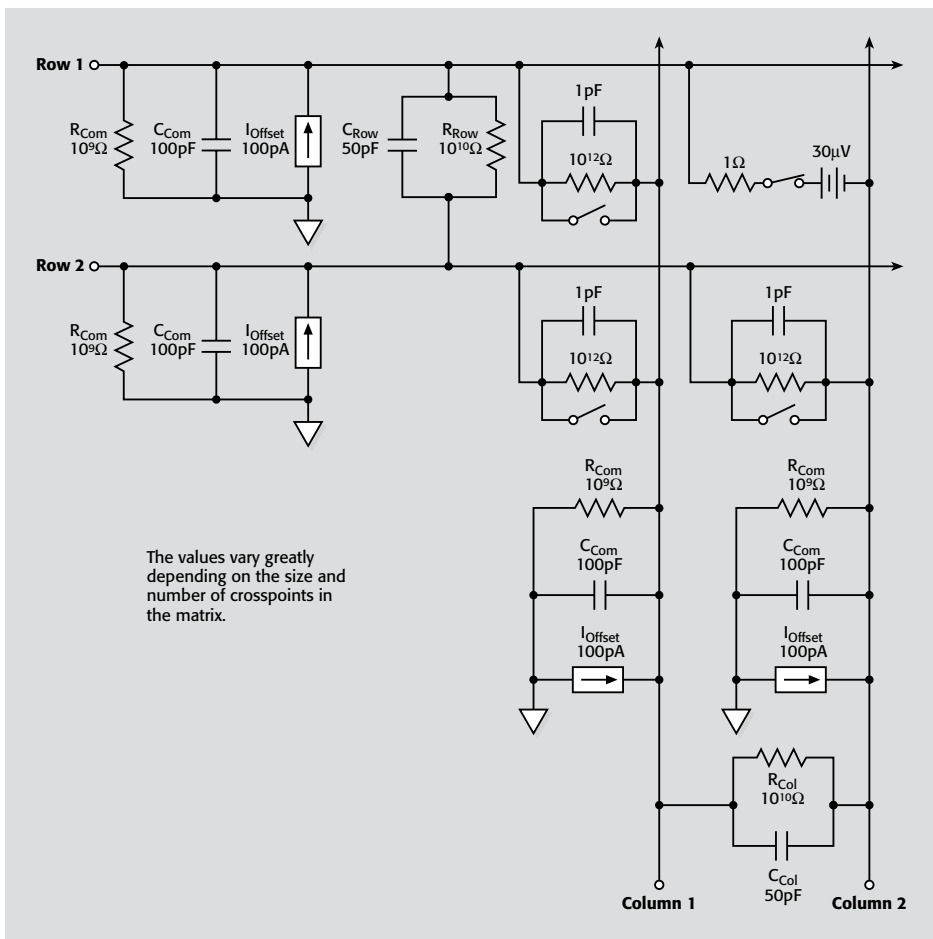
Figure 3-17. One-pole common low matrix

Another option for even higher performance is to use point-to-point wiring with driven guard triaxial cable. Separate, very high quality relays can be used with individual shielding added. In some cases, the reed (of the reed relay) is placed outside the center of the coil to improve electrical isolation.

The guarded switch can be used in all the topologies presented. The guard must be switched in scan, multiplex, and matrix configurations. Each DUT might need a different guard voltage. Since the guard is driven from a low impedance source, they cannot be connected together. **Figure 3-16** shows the guard requirement for a multiplex configuration. (Scan and matrix configurations are similar.)

One-Pole Common Low Matrix

Figure 3-17 shows a simple model of a one-pole matrix (LO is common for the entire system). Here again, distributed effects have been lumped into single value elements and, whenever possible, a single element. In the model, a current source (I_{OFFSET}), a resistor (R_{COM}), and a capacitor (C_{COM}) are shown between each row or column and common. These are the combined effects of relay and wiring leakages. Relay input effects are modeled on each row and relay output effects show up on each column. Their net effect is to reduce the input isolation specification.

Each row is also coupled to each column through the relay contact leakage resistance and capacitance. This increases the crosstalk (reduces the isolation) and allows signals from open crosspoints to get through. Finally, due to parallel wiring on rows and columns, each is coupled to the adjacent one(s) through R_{COL}, C_{COL}, R_{ROW}, C_{ROW}. These also add to the crosstalk and isolation problems.

Given the amount of parallel paths and relays on each signal line, isolation can degrade in a matrix configuration faster than with any other topology. Because of this, relays with very high insulation resistance and low contact capacitance are needed. The relays should also have excellent contact-to-coil shielding action. Many matrix switching systems use three-pole guarded relays and wiring. Guarding is the only practical way to achieve high channel-to-channel isolation and low leakage currents. This arrangement also allows the use of driven guards for sensitive measurements.

3.4 Mainframe Specifications

Mainframe specifications usually include parameters such as card capacity, memory, card compatibility, etc., most of which are self-explanatory. The following paragraphs discuss the analog backplane, triggers, and digital I/O in greater detail.

3.4.1 Analog Backplane

Many switch mainframes have an analog backplane that allows the outputs of a switch card in one slot to be connected to the outputs of other cards of the same model installed in other slots. The backplane eliminates the necessity of wiring the card outputs together externally. For certain signal types, such as low level or high frequency, the analog backplane should not be used to avoid possible signal degradation.

Refer to the specifications or operating manual of the switch card to determine if it can be connected to the backplane, because not all switch cards allow this.

If a particular switch card with no backplane connection is installed in a slot of the mainframe, it will be electrically isolated from other cards installed in the mainframe.

For some applications, it is necessary to disconnect a card from the analog backplane. Most switch cards have jumpers that can be removed to disconnect the card output from the backplane.

Some mainframes also have jumpers that can be removed to isolate certain groups of slots. For example, the Model 7002 Mainframe has a jumper that can be removed to isolate slots 1–6 from slots 7–12. Similarly, the Model 707A Mainframe has removable jumpers between slots 3 and 4.

3.4.2 Triggers

Most switch mainframes can be triggered externally via the trigger input and can send an output trigger pulse when the relay contacts have settled. Precise triggering is important in test system development to ensure synchronization between the switch system and other instruments in the system, such as sources and measuring devices.

An input trigger can be used to close an individual channel or to initiate a scan of several channels. Trigger sources include manual (front panel button), IEEE-488 bus, Trigger Link, internal timer, and external trigger.

The output trigger may be connected to a measuring device, such as a voltmeter. This will ensure the measurement is not made until the switch contacts have fully settled.

Specific details on triggering can be found in the operating manuals of the various mainframes.

3.4.3 Digital I/O

Scanner mainframes usually have a built-in digital I/O port for use with external digital circuitry, such as relay drivers, interlock switches, etc. The port provides both output and input channels, which are generally TTL compatible.

Digital outputs can be controlled from the front panel or from the bus controller. These outputs can be used to control a few external relays in case the scanner cards in the mainframe are already committed. The digital output can also be used to control an indicator light to let the operator know when the scan is in progress or when a test is complete.

The digital inputs allow the state of external digital signals to be determined by the controller. The digital input can be used in conjunction with an external safety interlock switch. For example, when a safety door is open, a signal will be sent to the scanner mainframe to prevent scanning until the door is closed.

If more digital I/O lines are required, then a digital I/O card, such as the Model 7020 (for the Series 7000) or Model 7707 (for the Series 2700), can be installed in the mainframe.

SECTION 4
Issues in Switch System Design

4.1 Introduction

Section 1 covers switching configurations and hardware options. Section 2 describes switching components. Section 3 addresses switch card and mainframe considerations. Section 4 outlines the fundamentals of switch system design. In addition, this section discusses issues such as calculating uncertainties, techniques for minimizing switching time, and the use of cold vs. hot switching.

When designing and selecting switching instrumentation, there are several important factors to keep in mind:

- Switching configurations available.
- Number of device pins and number of instruments.
- Electrical specifications.
- Speed.
- Control bus compatibility.
- Physical size.
- Flexibility (to adapt to changing system requirements).
- Base cost.
- Expansion cost.

4.2 Basic Steps for Switch System Design

In test and measurement system design, the process of selecting suitable switch hardware is extremely important, but is often underemphasized. The objective of any switch system is to transfer the accuracies and specified performance of the system instruments to the device under test. This section is intended to help engineers choose the appropriate switch hardware and develop a productive switch system design.

Before attempting to select the switch hardware, answer the following questions:

1. What is the purpose of the switching system? (For example, is it intended to make measurements, to route signals, or to connect a source to multiple samples?)

2. What is the magnitude of the signals being switched, and what is the required level of accuracy? (For example, are the signals high current, low voltage, high frequency, low current, high resistance, high impedance, etc.?)

3. How many instruments need to be routed to how many signals? (For example, are you connecting one voltmeter to ten batteries?)

4. What type of switching configuration will provide the best performance? (Matrix, multiplexing, scanning, or isolated switching? Refer to Section 1.4 for further details.)

5. What's the required operating speed? (For example, does it require scanning and measuring ten batteries within one second?)

6. Are the switch mainframe and cards compatible with other equipment in the system with respect to triggering, controls, and connections?

Once these questions are answered, create a schematic of the test system, including as much detail as possible. After reviewing the configuration, it may be possible to streamline the system. For example, testing four-wire resistors may require four switch poles per resistor. However, if a common connection can be made to one side of all the resistors, then only two switch poles would be needed per resistor.

Once this information has been gathered, determining the type and number of switch mainframes and cards required is straightforward. Consider several alternatives to find the best fit. In some cases, mixed signal types will limit the choice of switch cards. For example, it may be necessary for a system to route high voltage signals at some times and high current signals at others. In this case, there are a limited number of switch cards that can handle both the high voltage and the high current signals. Two separate groups of cards may be needed in these circumstances.

Once the hardware has been selected, evaluate the design again to ensure its adaptability to new applications for future system expansion.

4.3 Calculating Uncertainties

Once the switching hardware has been selected, it is important to calculate the uncertainties and speed of the system to verify that it meets all accuracy requirements.

When an unknown signal is connected to a measuring device, such as a voltmeter or ammeter, the measurement accuracy is almost entirely determined by the measuring device. However, adding a switching system to facilitate the connection between the signal source and the measuring instrument also adds measurement uncertainties. The switch card specifications can be helpful in determining the degree of uncertainty due to the switch card, but use only the specifications relevant to the particular application in error analysis.

For example, in a system for measuring small DC voltages, the contact potential of the switch will be added to the signal. A typical switch for this application may add from 200nV to 5μV per contact pair. When added to the signal, it's easy to calculate the impact of this contact potential on the measurement accuracy. However, switch contact potential will have very little effect on a system for measuring low currents. In this case, the offset current of the switch will be the dominant error source. Switches designed for low current applications may have offset currents from 100fA to 100pA. As with the contact potential, the uncertainty added to a small current signal by the offset current can be calculated.

A low current measurement system may also require significant settling time before the expected accuracy can be obtained. This time may be much longer than the specified relay settling time; it's usually determined by the resistance-capacitance (RC) time constant of the circuit or by experimentation. Settling time is discussed further in Section 4.4.

In addition to the sources, meters, and switch cards, uncertainties may arise due to the additional cabling and test fixturing associated with the switching circuit. For example, in low current and high resistance applications, unguarded cabling can introduce leakage current that will degrade measurement accuracy. Unshielded cable may result in noisy readings for low current and high resistance applications.

4.4 Switching Speed

Several factors can affect test system speed, including measurement time, the source response time, and the switching time. Switching time is the time required to disconnect from one signal and to connect to a second signal. It is the sum of three time factors:

- *Trigger Execution Time (trigger latency)*—This is the length of time, typically several hundred microseconds, from the activation of the trigger source to the start of switch opening or closing.

- *Relay Actuation Time*—This is the time from the application of relay coil voltage to the closure of the contacts, including contact bounce time. Actuation time, which ranges from 2 to 20 milliseconds, is typically called out in the card's specifications.

- *Settling Time*—This is the time required for the circuit to stabilize once the relay has been closed.

Figure 4-1 illustrates the relationship between these three factors.
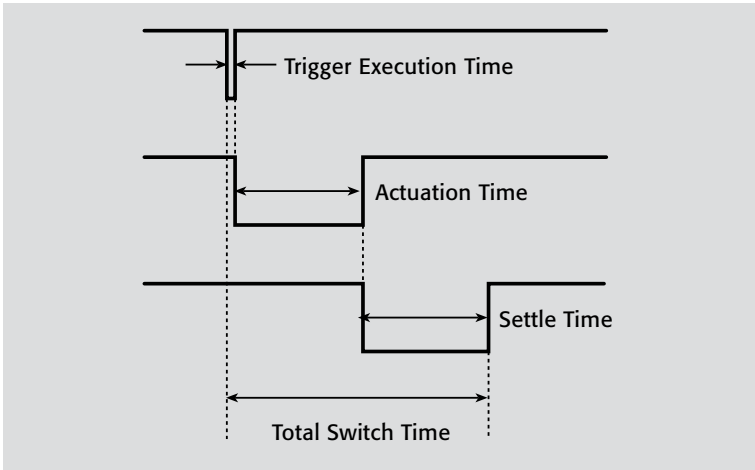
Figure 4-1. Total switching time

Settling time can best be illustrated with an example. In **Figure 4-2**, the R represents the series resistance and the C represents the shunt capacitance. When the switch is closed, the time required for the capacitor to charge up to 63% of the final value is equal to the RC time constant, which can be calculated as:

$\tau = RC = 10k\Omega \times 185pF = 1.85\mu s$
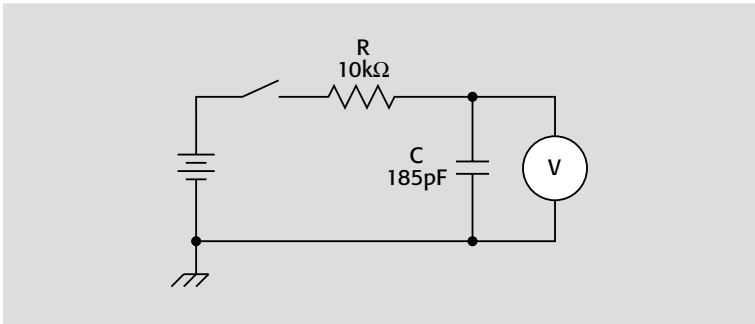
Figure 4-2. RC circuit

To achieve the desired accuracy, it may be necessary to wait several time constants. For example, to settle within 1% of the final value, it will require 4.6 time constants or $8.5\mu s$.

The system throughput includes these timing factors, as well as the timing factors associated with other instruments in the system. For example, the voltmeter trigger time and measurement time would also be included in the total system time.

To increase overall system speed, synchronize all the instruments in the system using hardware triggers. Hardware triggers are usually much faster than software triggers because software triggers must first be parsed/processed before being sent to the instrument.

To avoid delays due to computer overhead, use the internal memory of the scanner or the "scan lists." These lists or set-ups are stored in the memory of the scanner and can then be recalled much faster than sending individual commands to open or close channels.

If possible, set built-in trigger delay times to the minimum allowable time, preferably zero seconds.

4.5   Cold vs. Hot Switching

The term "cold switching" indicates that a switch is actuated with no applied voltage; therefore, no current will flow when the switch is closed, and no current will be interrupted when the switch is opened. When "hot switching," voltage is present and current will flow the instant the contacts close. When the switch is opened, this current will be interrupted and may cause arcing.

Cold switching allows power to be applied to the device under test in a controlled manner. Its primary advantage is that the life expectancy of the switches is much greater than with hot switching. Cold switching also eliminates arcing at the relay contacts and any RFI that might be caused by arcing.

Hot switching may be required when the interval from when power is applied to the point when the measurement is made must be closely controlled. For example, hot switching is typically used where digital logic is involved, because devices may change state if the power is interrupted even for a brief instant.

With relatively large relays, it is even possible that hot switching must be used to ensure good contact closure. The connection may not be reliable without the "wetting" action of the current through the contacts.

Cold switching is desired to extend contact life. It can increase contact life by 10–1000 times over switching at maximum levels. Cold switching avoids unintentional make-before-break problems (momentary shorts between devices). It is also desired to reduce transients when switching sensitive loads (DUTs or instruments) and capacitive loads.

Figure 4-3 shows an example of channel resistance versus contact life for the Model 7075 General Purpose Matrix Card. The card is specified at <0.5Ω initial channel resistance and <1.5Ω channel resistance at end of contact life.
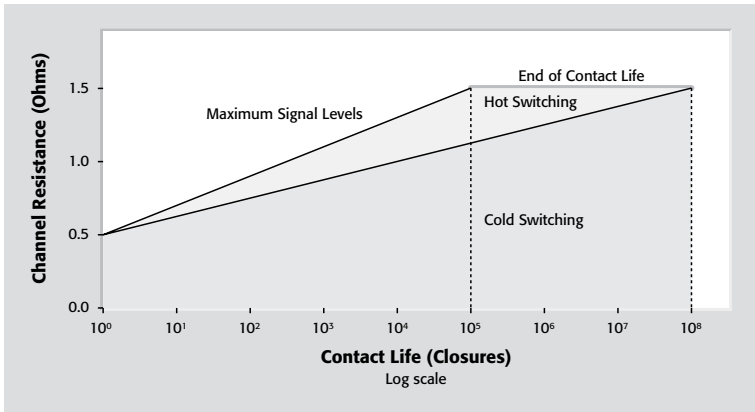
Figure 4-3. Model 7075 channel resistance versus contact life

As the specifications state, if cold switching is used instead of hot switching at maximum signal levels, contact life is extended from 10^5 closures to 10^8 closures. Switching at less than the maximum signal levels yields a contact life between 10^5 and 10^8 closures. Approximating where in that range can be estimated by measuring the channel resistance.

Some switching cards, such as those having electromechanical relays for the Keithley Series 2700 Multimeter/Data Acquisition/Switch Systems and Series 3700 System Switch/Multimeter, have onboard memory that acts as a contact closure counter. This feature allows for proactive maintenance for relay replacement.

4.6 Switch Systems with Built-in Multimeters

In recent years, a growing number of manufacturers have combined switching and measurement functions in the same instrument. For many applications, this approach offers a variety of testing advantages by eliminating many of the complexities of triggering, timing, and processing issues. It also offers cost advantages for lower channel count applications by allowing system builders to create a complete scan and measure system with just a single instrument and a few plug-in cards. For example, Keithley's Models 2000 (6½ digits), 2001 (7½ digits), 2002 (8½ digits), and 2010 (7½ digits) Digital Multimeters feature a built-in scanner mainframe designed for plug-in cards that provide up to ten (two-pole) analog input channels. The 6½-digit Series 2700 Multimeter/Data Acquisition/ Switch Systems are designed to accommodate applications that require greater switching capacity. The Models 2700 and 2701 are capable of handling 80 differential input channels or 96 matrix crosspoints; the Model 2750 can accommodate up to 200 differential input channels or 240 matrix crosspoints.

The Series 3700 System Switch/Multimeter line carries this trend forward, with an optional integrated 7½-digit DMM and six switch card slots that can accommodate up to 576 multiplexer channels or matrix crosspoints.

4.7 TSP™ and TSP-Link™

TSP-based instruments such as the Series 3700 System Switch/Multimeter incorporate several technologies designed to simplify creating multi-channel I-V test systems economically. In addition to an embedded Test Script Processor (TSP™), these instruments include TSP-Link™, a high speed trigger synchronization/inter-unit communication bus, which test system builders can use to connect multiple instruments in a master/slave configuration. In a TSP-Link-enabled system, one instrument (the unit that is connected to a communication bus such as GPIB, USB, or Ethernet) is considered the master. A TSP script runs on the master instrument and controls the slave unit(s): one script program controls both the master and any connected slaves.

Essentially, a script is a collection of instrument control commands and/or program statements. Program statements control script execution and provide facilities such as variables, functions, branching, and loop control. Because scripts are programs, they are written using a programming language. This language, called the Test Script Processor language, allows users to create powerful, high speed, multi-channel tests with significantly reduced development times. TSP scripts can be downloaded into either volatile or nonvolatile memory of a TSP-enabled master instrument and the unit controls itself and any slaves, independent of the system host controller. This capability can free up the system controller to interface with other instruments in the rack more frequently, thereby increasing the overall system throughput.

Master/slave operation is much faster than sending commands and trigger signals back and forth between the controller and the individual instruments in the test configuration over a traditional communications bus and helps reduce programming complexity. Once connected via TSP-Link, all the TSP-equipped instruments in a system can be programmed and operated under the control of the master unit or units, just as if they were all housed in the same chassis.

When multiple instruments are connected via TSP-Link, they can be operated like they are part of the same physical unit for simultaneous multi-channel testing, which offers dramatic throughput advantages over accessing multiple instruments sequentially. For example, multiple Model 3706 switch/DMMs can be daisy-chained together to create a system with many channels, all of which respond to commands issued by the TSP of a single master unit. All the other
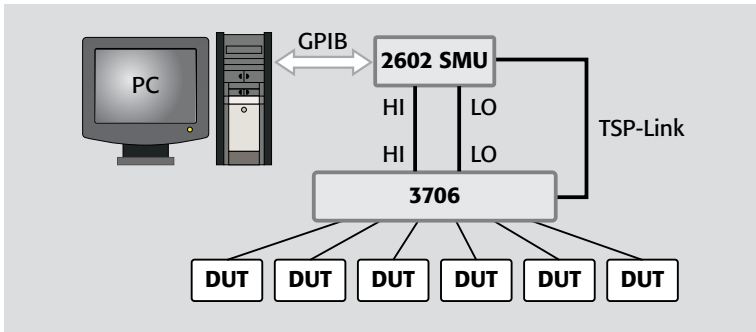
Figure 4-4.

TSP-Link connected Model 3706s are treated as extensions of the master, so it's only necessary to create one script to run on the master instrument.

In the test system configuration shown in **Figure 4-4**, the instruments are connected through TSP-Link, with a Model 2602 System SourceMeter instrument acting as the master and the Model 3706 acting as the slave. The user need only program the Model 2602; the script running on its embedded TSP directs the operation of the Model 3706's switches via the TSP-Link connection. Unlike many earlier Keithley instruments, the Model 3706 and Model 2602 do not employ a trigger model, a feature that provides a flexible structure that describes how the instrument responds and operates in terms of timing, triggering, number of data points to measure per trigger event, etc. The Model 3706 and 2602's scripting capabilities mean that no trigger model is required because the script can be configured to match the need of the application exactly.

This approach to programming incorporates the concept of a "table" or variable. The table can include anything, but it makes sense in this case to use an array of data, in this case, a list of switch channels through which the system can scan. Obviously, this is far less time-consuming than sending one command at a time to execute each channel closure. The following example table, which is named "mem pattern", is an array of 10 channels.

```
mem_pattern = {"2001", "2002" ,"2003", "2004", "2005",
"2006", "2007", "2008", "2009", "2010"}
```

The following script, designed to be downloaded to the master Model 2602's TSP, uses a loop to step through each channel in the array. Various TSP commands for switching, such as channel.open and channel.exclusiveclose are included, along with various source and measure commands, such as

`smu.source.rangev`, `smu.measure.i`, and `smu.source.levelv`. Notice the table "`mem pattern`" is used in the script.

```
for i = 1,10 do
     slaveNode37xx.channel.exclusiveclose(mem_
pattern[i])
     smu.source.levelv = sourceLevelV
     delay(sourceSettleTime)
     smu.measure.i(bufferSMU)
     smu.source.levelv = 0
end
```

This script is essentially a set of instructions to the Model 2602 and Model 3706 to perform these tasks:

1. Do loop of 10 iteration.

2. Close first channel in the table "mem pattern."

3. Set SourceMeter to source 1V.

4. Short delay.

5. SourceMeter to read the data and place in bufferSMU.

6. Set source level of 0V.

7. Do this 10 times, until end of the do loop.

The only function of the computer controller in this test configuration is to download the test script to the Model 2602's TSP. All communication between the Model 2602 and the Model 3706 is conducted via the TSP-Link. Once the script has been downloaded to the master unit, no bus traffic is involved until it's time to upload test data to the computer controller for analysis. By eliminating the constant GPIB bus traffic common in more traditional test system configurations, TSP and TSP-Link can dramatically reduce test times by allowing tighter integration between the various switching, sourcing, and measuring instruments. As a result, TSP/TSP-Link-based systems are ideal for high throughput production test applications.

SECTION 5

Switch Considerations by Signal Type

5.1   Introduction

The quality of a switch system depends in large part on its ability to preserve the characteristics of the test signals routed through it. For example, when the test signal is a low voltage, the switching system must minimize errors such as offset voltage and IR drops. Leakage current may be a problem for high resistance and low current switching applications. Depending on the type of test signal involved, specific switching techniques must be used to maintain signal integrity through the switch system. This section describes switching techniques for a variety of test signals.

5.2   Voltage Switching

Many different applications involve switching a voltmeter or voltage source to multiple devices, including testing batteries, electrochemical cells, circuit assemblies, thermocouples, etc.

The types of switch cards and the techniques used in these applications will depend on the magnitude and impedance of the voltages switched. The approximate level for low voltage switching is in the millivolt range or less, mid-range levels are from 1V to 200V, and voltages greater than 200V demand the use of high voltage switching methods. This section describes the mid-range voltage switching techniques. See Section 5.2.1 for a description of low voltage switching techniques, Section 5.2.2 for high voltage, and Section 5.2.3 for high impedance voltage switching.
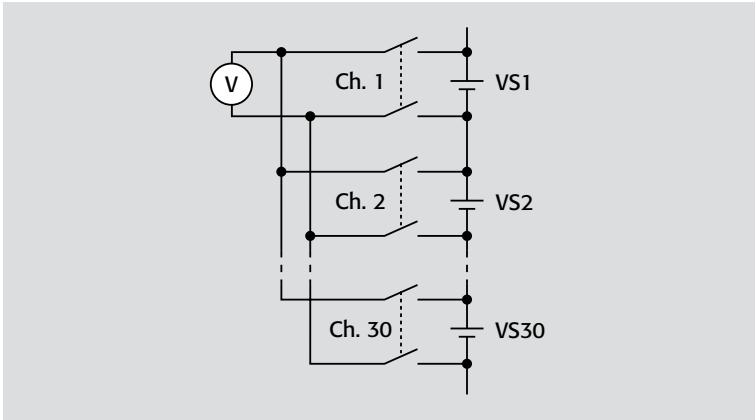
Switching multiple sources and switching multiple loads each have their own sets of associated problems.

Switching a Voltmeter to Multiple Sources in Series

Figure 5-1 illustrates switching a voltmeter to a series string of 30 batteries or voltage sources (VS). To avoid short-circuiting one or more of these sources, it is necessary to open a given channel before closing a second one (break-before-make operation). To guard against short-circuiting, add fuses in series with each voltage source to prevent damage to the switch card. Be sure not to exceed the common-mode rating of the switch card. In this example, each battery is 12V and the total voltage across the string is 360V. A channel-to-channel voltage rating and a common-mode voltage rating of at least 500V is desirable.
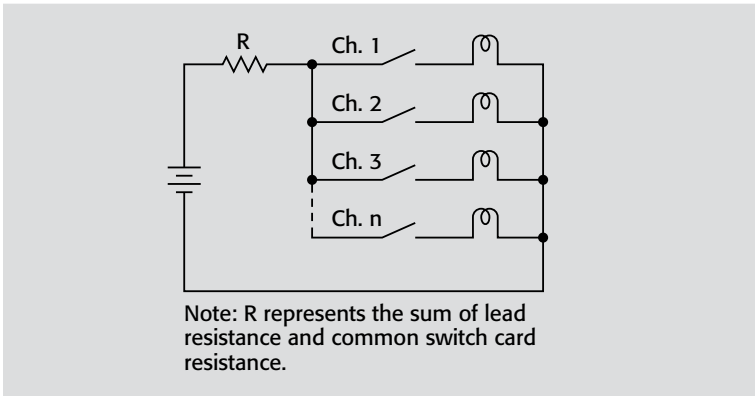
Switching a Voltage Source to Multiple Loads

Figure 5-2 shows a single voltage source connected to multiple loads, such as lamps. If two or more loads are connected to the source, the voltage at each load

Figure 5-1. Switching a voltmeter to multiple sources in series

may be less than expected due to current flow through the common impedances (R), such as the test leads and trace resistance. As additional loads are connected, the total current will increase, thereby increasing the voltage drop across the common impedances (R).

Note: R represents the sum of lead resistance and common switch card resistance.

**Figure 5-2. Switching a voltage source to multiple loads**

Switch Resistance

When switching a voltage source to multiple devices, it may become necessary to compensate for voltage drops due to switch resistance. In particular, if the devices have low resistance, the current flowing through the switches may cause a significant voltage drop. To prevent this problem, remote sensing can be used to correct for any voltage drops in switches and wiring. With remote sensing,

external sense connections are made across the load. Therefore, the subsequent programmed output voltage will be the actual voltage across the load.

For example, **Figure 5-3a** shows a 5V source being switched to an integrated circuit (IC). The contact resistance for each switch is 1Ω. If the current drawn from the source is 500mA, the voltage drop across each switch will be 500mV, and the voltage at the integrated circuit will be reduced by a total of 1V. Operation of the IC will likely be unsatisfactory. **Figure 5-3b** shows a 5V source with remote sense. In this case, sense leads are also connected to the load. This will ensure that the actual voltage across the load will be 5V, and the IC will operate as intended. Note that the voltage at the source output terminals is 6V.

Do not use hot-switching with remote sensing since the voltage from the source may become excessive during switching.
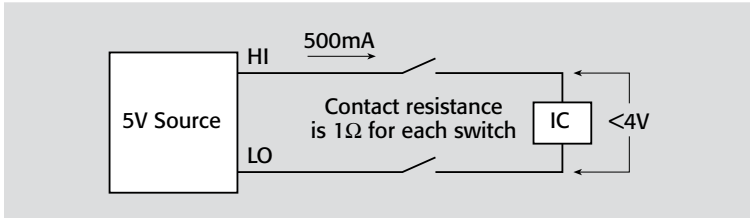
Figure 5-3a. Voltage drops across the contact resistance cause improper results
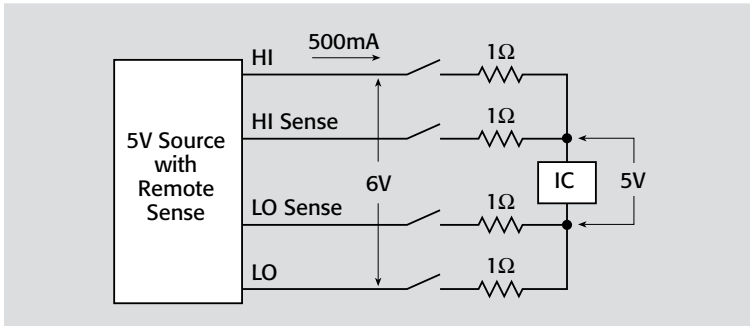
Figure 5-3b. Using remote sense through a switch ensures the proper voltage delivered to the IC

5.2.1 Low Voltage Switching

When switching low voltage signals (millivolts or less), special techniques must be used to avoid unwanted voltage errors. However, the required accuracy will determine if these techniques are necessary.

These unwanted voltage errors may be due to thermoelectric offset voltage in the switch card and connecting cabling, switch film contamination, magnetic interference, and ground loops. These sources of interference and ways to eliminate or reduce them are discussed in this section. For more information on low voltage measurements, refer to Keithley's *Low Level Measurements Handbook*.

Thermoelectric Offset Voltage

The contact potential or thermoelectric offset voltage is the key specification of a switch card designed for low voltage switching. Thermoelectric voltage is the voltage generated by thermal differences at the junction of dissimilar metals, such as between the nickel-iron reed relays and the copper conductor to which they are connected. The temperature gradient is typically caused by the power dissipated by the energized coil. The offset voltage adds directly to the signal voltage and can be modeled as an unwanted voltage source in series with the intended signal. The offset voltage will cause an error in the applied stimulus to a device under test or the value measured by the voltmeter.

As shown in **Figure 5-4a**, the offset voltage (E) of a single pole relay is added into the circuit. As a result, the measured voltage (V_M) will be the sum of the source voltage (V_s) and the offset voltage (E). To minimize this offset voltage, a low voltage switch card uses a two-pole relay, as shown in **Figure 5-4b**. Here, the
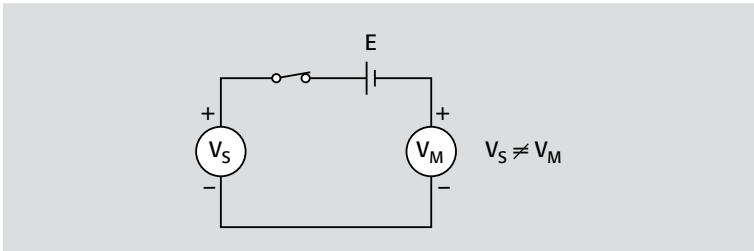
Figure 5-4a. Potential in loop is added to measurement
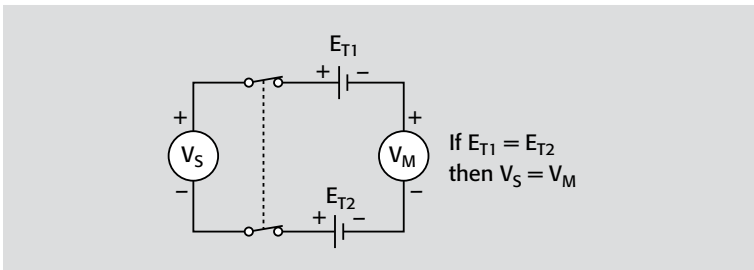
Figure 5-4b. Canceling of potentials in loop

offset voltage (E_{T1}) in the circuit HI is largely canceled by the offset voltage (E_{T2}) in circuit LO. The contact potential of some low voltage cards is specified with the card used as a two-pole switch to take advantage of this cancellation. It may be specified as "per contact pair." However, total cancellation cannot be achieved because temperature differences will cause E_{T1} and E_{T2} to be slightly different.

The drift due to the thermoelectric voltage of a switch card depends on several factors, including the type of relays used (reed, solid-state, or electromechanical). The drift also depends on the coil drive technique (latching or non-latching). Finally, the material used for the contact plating (for example, nickel alloy or gold) also affects the thermoelectric voltage, as described in Section 3.2.6.

The power dissipated in the coil of the reed relay may cause the temperature to increase for several minutes after it is energized, so it is important to make low voltage measurements within a few seconds after contact closure. If many measurements are taken over several minutes after closure, a steadily increasing thermoelectric voltage will be added to the reading. Thermal time constants may range from seconds to hours. Even though solid-state relays have no coil dissipation, heat generated by internal IR drops can still produce thermoelectric drift. Latching relays use a pulse of current to actuate them, so they have very low thermoelectric drift.

The connections to the switch card itself represent another source of thermally generated voltages. Wherever possible, make connections to the card with untinned copper wire, and keep all leads at the same temperature.

The thermoelectric offset voltage due to the switch card and the interconnecting cable may be compensated for by using a short-circuited channel to establish a zero reference. Connect a clean copper wire connected between the HI and LO terminals of an unused channel. Close the channel and measure the offset voltage. Then open this channel. This value can be subtracted from subsequent readings made on other channels. This approach is not ideal because the offset will change over time due to self-heating and changes in the ambient temperature.

When switching low voltages while making low resistance measurements, the thermoelectric offset voltages may be canceled by using offset compensation. This technique requires making two voltage measurements with two different values of current. To determine the resistance, the difference between the two resulting voltages is divided by the difference of the two test currents:

$$R = \frac{V_1 - V_2}{I_1 - I_2}$$

Section 5.4.1 offers more information on this method.

Switch Film Contamination

Over time, a contaminating film can form on the surface of a relay contact. This film can increase the relay contact resistance, which can make the switched voltages erratic when measuring or sourcing low voltage. Voltages greater than 100mV are usually sufficient to clear this contamination. Using scanner cards with solid state switches is one way to avoid this problem.

Magnetic Interference

Magnetic interference can be a problem in low voltage circuits. A high rate of change in magnetic flux, such as that produced by a switching power supply or by switching a high current signal on and off, can induce a pulse of many microvolts in an adjacent circuit. This can easily cause significant error in a low voltage circuit. This type of interference can be minimized by separating the noise source and the sensitive circuit as much as possible, by magnetic shielding, and by reducing the enclosed area of the noise source and signal conductors. Twist the HI and LO wires of each channel together to minimize the enclosed area.

Ground Loops

Ground loops can easily occur in a complex test system. If a small potential difference exists between two ground points, some ground currents may flow through a sensitive part of the system. This may occur only when certain switches are closed, so it can be very difficult to diagnose. When possible, try to maintain a single system ground point. When this is not possible, isolation techniques using optical coupling or balanced transformers may help by increasing the effective resistance between the two points, thereby reducing the common ground current to a negligible level.

5.2.2 High Voltage Switching

Some applications, such as testing insulation resistance of cables and printed circuit boards and high-pot testing, may require switching high voltages. To avoid switch card damage, be particularly careful when switching voltages of ~200V or higher.

Choose a card rated for the desired voltage and power levels. Cold switching, if feasible, will extend the relay life and make it possible to increase the allowable current. Be sure to use appropriately rated cables when switching high voltages.

Reactive loads can cause excessive current and voltage transients, so current surge limiting for capacitive loads and voltage clamping for inductive loads are required to prevent damage to the relays and external circuitry.

The surge current from a capacitive load is $i = C\ dV/dt$ and must be limited to less than the rated current to protect the relays. **Figure 5-5** shows a series resistance (R) used to limit the charging current. The resistor must be able to withstand the applied voltage; otherwise, the high voltage may arc across the resistor, damaging the device under test and the switch card. All components must be rated for peak voltage and current.

When determining the current limit for a reactive load, consider the maximum load in VA. For example, if the maximum load is 10VA and 500V is switched, then the current must be limited to 20mA. The series resistance is then calculated as:

$$R = \frac{500V}{20mA} = 25k\Omega$$
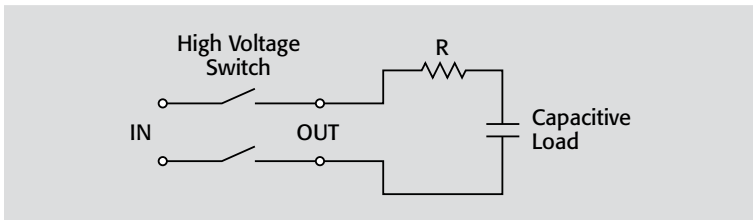
Figure 5-5. Limiting capacitive reaction current
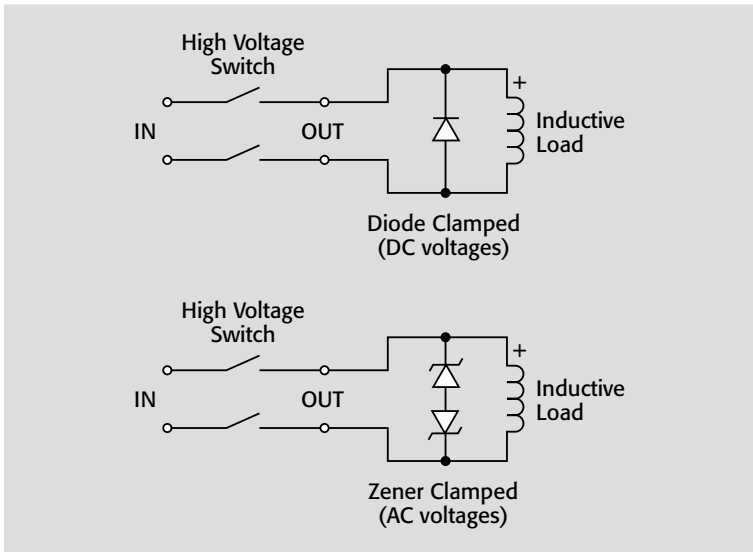
Figure 5-6. Limiting inductance reaction voltage

Inductive reaction voltage (L(di/dt)) must be less than the scanner card's maximum voltage rating. **Figure 5-6** shows two typical clamping circuits, one using a diode for clamping DC voltages and the other using back-to-back zener diodes for clamping AC voltages.

5.2.3 High Impedance Voltage Switching

High impedance voltage switching may be necessary in applications such as monitoring electrochemical cells and measuring semiconductor resistivity. Switching and measuring voltage sources with high internal impedance are subject to a number of errors, including offset currents, stray leakage paths, and electrostatic interference. Shunt capacitance may increase the settling time. This section discusses these error sources and provides an example application.

When choosing a card to switch high impedance voltage, make sure the card has a low offset current. Any offset current flowing through a high impedance device will cause an unwanted voltage to appear across the device. This offset voltage will be added to the voltage measurement.

High impedance circuitry is susceptible to electrostatic interference, so use shielding to avoid noise pickup. The device under test, as well as the connecting cables, should be well shielded.

Leakage paths can cause error by reducing the measured voltage. Such leakage paths may be present in the test instrument, switching cards, cables, and fixtures. To minimize errors due to such leakage paths, choose a switch card with high isolation resistance and use guarding wherever possible, including in the test fixturing and cabling. Also, select insulating materials with the highest possible insulation resistance.

Further information on offset current, electrostatic interference, and leakage currents can be found in Section 5.3.2 and in Keithley's *Low Level Measurements Handbook*.

Response time is another concern when switching high impedance voltage signals. Excessive response time may be caused by shunt capacitance, both in the switch itself and in the associated cables. In some cases, the shunt capacitance can be largely neutralized by the use of a driven guard, which will keep the shield of the cable at nearly the same potential as the center conductor (or high impedance lead) of the cable. **Figure 5-7a** shows a high impedance voltage connected through a switch to an electrometer voltmeter. Notice the slow response to a step function. To guard the signal, make a connection between the guard output (unity gain or preamp output) of the electrometer and the shield of the switch

card, as shown in **Figure 5-7b**. Some electrometers, such as Keithley's Model 6517A and Model 6514, can make this connection internally by enabling the internal guard connection. Enabling the guard effectively reduces the cable and switch capacitance, thereby improving the electrometer's response time.
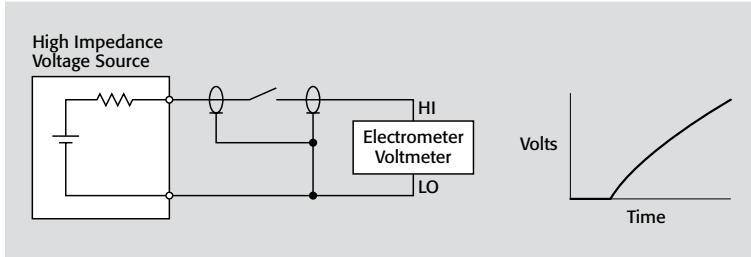
Figure 5-7a. Switching a high impedance voltage source to an electrometer
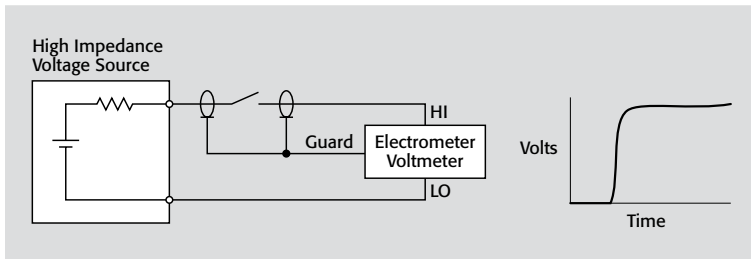
Figure 5-7b. Using a driven guard to neutralize shunt capacitance

Switch cards appropriate for high impedance voltage switching include the Models 7158 and 6522. A card with triax connections is necessary if the guard voltage could exceed 30VDC. This precaution is necessary to ensure safety.

5.3 Current Switching

Applications for current switching include testing of power supplies, insulation resistance, capacitor leakage, resistivity of materials, batteries, and semiconductors. This section discusses current switching in general. Special techniques are required when switching high current or low current. These techniques are discussed in Section 5.3.1 (High Current) and Section 5.3.2 (Low Current). Section 5.3.3 is a discussion of switching low current through a matrix.

Current switching applications may require connecting multiple current signals to a single meter, or may require connecting a single source to multiple loads. Each case has different switch configurations and concerns.

### Connecting Multiple Current Signals to a Single Ammeter

Most current measuring applications require that all current paths be continuous, even when a particular current signal is not connected to the ammeter. To accomplish this, switch cards designed for current switching often use SPDT or Form C relays. As shown in **Figure 5-8**, when a channel is in an open state (i.e., not connected to the output), signal HI is connected to signal LO through the normally closed (NC) contact. In this case, only signal HI is switched. Signal LO is hardwired to the ammeter and to all other signal LOs. This is normally the case when testing components with relatively low currents ($<1\mu A$). When a channel is selected, the current source is connected to the ammeter through the normally open (NO) contact. Note that the current will be interrupted briefly when the Form C relay is actuated. This could cause problems when used with high speed logic or other circuits sensitive to a momentary break in the current flow. This problem can be overcome by using a switch card with a pair of Form A isolated switches to provide a make-before-break (make/break) connection.
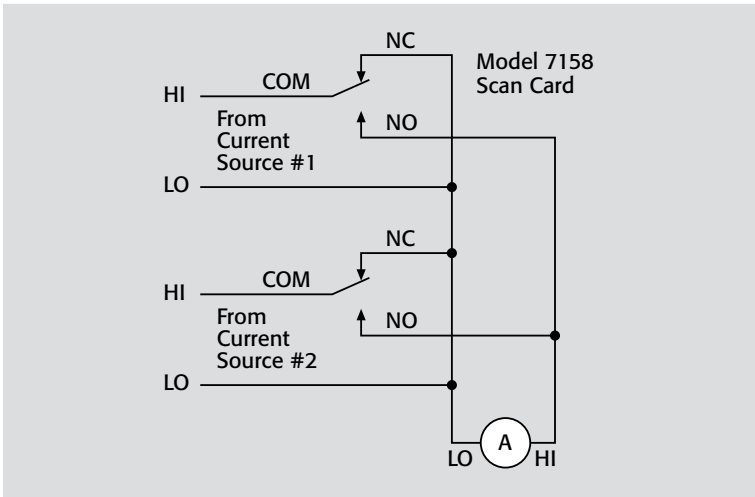
Figure 5-8. Using Form C relays to switch multiple current sources

Figure 5-9 illustrates using a switch card with isolated Form A relays to maintain the current path. In this example, one relay (Ch. 1) is used to connect Current Source #1 to the ammeter. A second relay (Ch. 2) is kept in the closed position to provide a path when the current is not being measured. If using a card such as the Model 7013 Relay Switch Card in a Series 7000 mainframe or the Model 3740 Isolated Switch Card in the Model 3706 mainframe, Ch. 2 is normally energized. This relay is opened when the measurement is made, but not until after Ch. 1 is

closed. This circuit is used when switching moderate-level current (milliamps to amps range) when the current cannot be interrupted even for a moment. Note that with this circuit, the LO terminals of the current sources are isolated from each other, unlike the circuit in **Figure 5-8**.
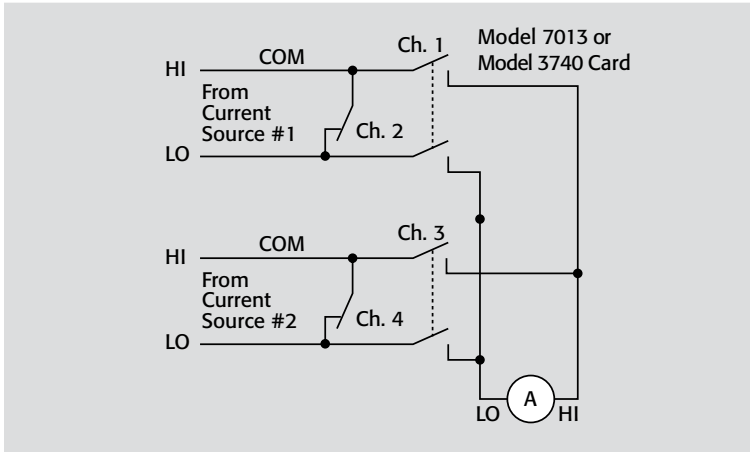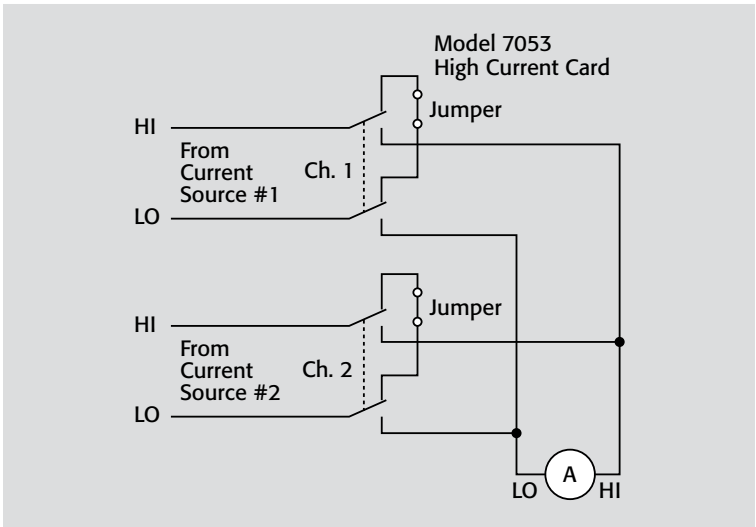

Figure 5-9. Using the Model 7013 Relay Card to switch current

The Model 7053 High Current Card is another card that is often used to switch current. As shown in **Figure 5-10**, this card uses a dual Form C relay. The jumper ensures a continuous path, but it can be removed when using the card to switch voltage. Because this is a Form C relay, the current will be momentarily interrupted when the relay is energized or de-energized.

An alternative to switching the current loop is to place a shunt resistor in the loop. The voltage drop across the resistor (R_S) is then measured as shown in **Figure 5-11**. The voltage readings are then converted to current using Ohm's Law. This technique can be used when the range of current is relatively narrow, such as approximately two decades. The resistor (R_s) should be no greater than the ratio of the maximum allowable voltage drop to the maximum current. Choose a value with a convenient scale factor, such as 1, 10, or 1000Ω, so that it will be easy to calculate the current. Once the value of the resistor is chosen, verify that the minimum voltage drop will not be so small that it will be difficult to measure with the voltmeter.

Connecting a Current Source to Multiple Loads

Unlike switching current signals to an ammeter, switching a current source to multiple loads usually does not require maintaining the current path at all times.

Figure 5-10. Using the Model 7053 High Current Card to switch current
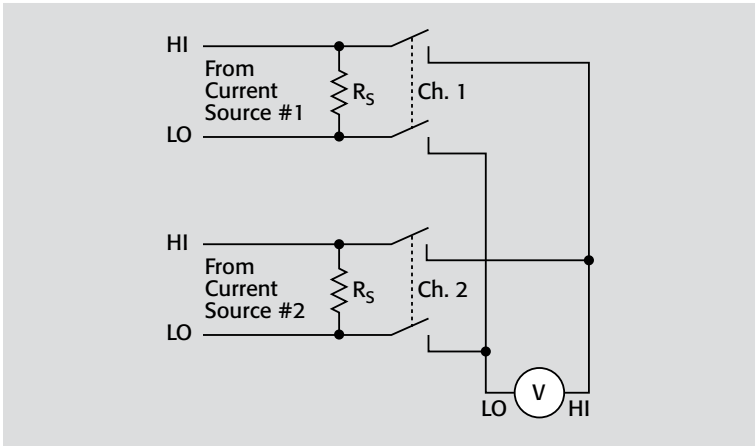
Figure 5-11. Using shunt resistors to measure current

For this case, a card with Form A switches is suitable, as shown in **Figure 5-12**. To connect the current source to Load #1, close relay Ch. 1. Ensure that Ch. 1 is opened before Ch. 2 is closed if the loads are capable of storing energy, such as a battery or a large capacitor. Two high energy loads connected in parallel may damage the relays.
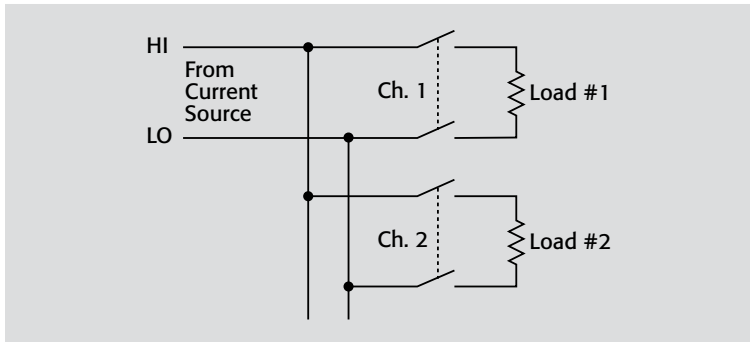
Figure 5-12. Connecting a current source to multiple loads

Often, cards designed for voltage switching can be used for current switching for currents from 1A to 1μA. For current less than 1μA, choose a card that has high isolation resistance (across open contacts, from high to low, and between channels) and low offset current.

Cold switching is always preferable to ensure maximum relay life. Cold switching involves turning the source current off (placing it on standby) before opening or closing a relay.

5.3.1 High Current Switching

When designing a switching circuit for high current (>1A), pay particular attention to the maximum current, maximum voltage, and VA specifications of the switch card. Also, it's important to choose a switch card with low contact resistance to avoid excessive heating that can cause contact failure by welding the contacts together. Contact heating is caused by I^2R power dissipation.

High current switching can be used for either switching a power supply to multiple loads or for switching an ammeter to multiple sources. **Figure 5-13** is an example of switching a power supply to multiple loads using a multiplexer scanner card. In this example, the power supply will output 1A to each of four loads. This doesn't present a problem when only one channel is closed at a time. However, when all four channels are closed, the power supply will output 4A through the common path. Unfortunately, even though the maximum current of a particular channel is specified at 1A, the common path on the switch card may not be able to tolerate 4A. This is not usually specified for a switch card, but the limitation is usually a function of the trace width and connector ratings. One way to avoid this problem is to use a switch card with independent (isolated) relays and connect with wires rated to carry the total current.
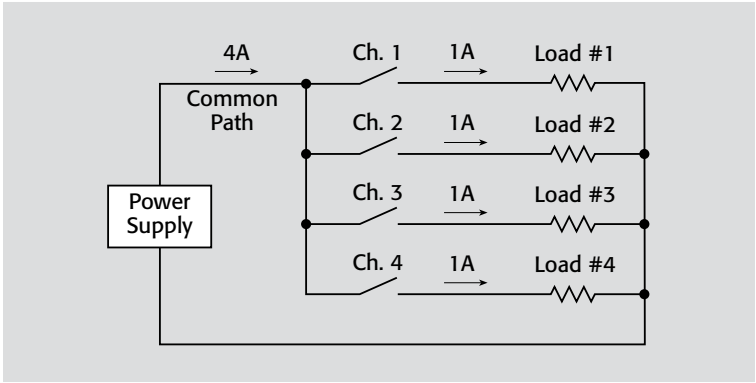
Figure 5-13. Switching a power supply to multiple loads

When currents that exceed the commercially available card ratings must be switched, then a general-purpose switch card can be used to control external high current relays or contactors. The user must supply the coil current for the external relays.

Under no circumstances should unlimited power (direct from the power line) ever be connected directly to a switch card.

When switching high VA loads (power line to motors, pumps, etc.), solid-state relays (SSR) are often used. Industry standard SSR modules are available from many sources. These SSR modules are plugged into a board, such as the Keithley Model PB-24SM, that can be controlled from TTL-level digital outputs. These

Table 5-1. High Current Switches

Card Model	Current Rating	Compatible Mainframes
7053	5A (10 channels)	7001, 7002
7700	3A (two channels)	2700, 2701, 2750
7702	3A (two channels)	2700, 2701, 2750
7705	2A (40 SPST Isolated)	2700, 2701, 2750
3740	3A (28 SPST Isolated) 7A (4 SPST Isolated)	3706
3721	2A switched, 3A carry (40 channels) 3A (2 channels)	3706
3730	6×16 Matrix (1A switched, 2A carry)	3706
7174A	2A carry	707A/708A

digital outputs can be from a board that plugs into a PC or from a scanner mainframe. Some SSR modules can switch up to 1kVA to high power loads.

Concerns about switching transients with reactive loads also apply to high current switching. Refer to Section 5.5 for more information on switching reactive loads.

Cold switching, where contacts do not make or break current or voltage, is recommended for currents in excess of 100mA to avoid radiated interference and to extend relay life. Refer to Section 4.5 for more information on cold versus hot switching. See **Table 5-1**, High Current Switches.

5.3.2 Low Current Switching

When switching currents of $1\mu A$ or less, special techniques must be used to minimize interferences, such as offset currents, leakage currents, electrostatic interference, triboelectric currents, and electrochemical currents. These types of interferences may be due to the scanner card itself, the connecting cables, or the test fixturing. Allowing sufficient settling time before making a measurement is also crucial when switching low current. Information on low current switching through a matrix is discussed in Section 5.3.3.

Offset Currents

The offset current specification of the switch card should be as low as possible for switching low current. Offset current is a spurious current generated by a switching card even though no signals are applied. It is usually caused by galvanic sources on the card. Offset current is especially significant when measuring low currents if the magnitude of the offset is comparable to the low current being measured. Scanner cards designed to minimize offset current are commercially available. For example, the Model 7158 Low Current Scanner Card has <1pA offset current (typically <30fA).

To measure the offset of a switch card, connect the output of the card to a picoammeter or electrometer. Make sure all input connections on the scanner card are shielded. If the card has triax or BNC connections, cap each input channel. Close each channel individually and measure the offset current after allowing the switching transients to decay and the current to stabilize. If the offset currents for the different channels are reasonably stable, a correction factor can be stored in the control computer to allow more accurate low current measurements. This is done by subtracting the offset current for a given channel from subsequent measurements made via that channel.

Leakage Currents

Leakage current is an error current that flows through insulators when a voltage is applied. It can be found on the switch card, in the connecting cables, and in the test fixture. Even high resistance paths between low current conductors and nearby voltage sources can generate significant leakage currents. Use a card with high isolation, guard the associated test fixtures and cables, select proper insulating materials, and clean the circuit boards to reduce these effects.

To minimize extraneous current paths (or leakage current), use a switch card that has high channel isolation resistance (the isolation between channels). When switching a current to be measured, high input isolation (the isolation between input HI and LO), is not as critical as channel isolation because there is normally very little voltage present, only the voltage burden of the ammeter. However, when switching a current source, very high voltage can be present across the input depending on the load resistance; therefore, high input isolation becomes critical.

To determine the leakage current at a particular voltage, apply a step voltage of this magnitude to the circuit. This generates a transient current that will gradually decay to a steady value, which is the leakage current of the system for that particular path. Once the leakage current is determined, it can be subtracted from subsequent readings on a particular channel. However, the leakage current is dependent on the applied voltage, so this technique cannot be used for voltage sweeps.

To prevent leakage current on the switch card, take special care when handling to prevent degradation of performance. Handle the switch card by the edges to avoid contaminating it with dirt, body oil, etc. If cleaning the board becomes necessary, follow the instructions in the manual provided with the switch card. Humidity can also increase leakage current. Placing the switch system in a low humidity room will minimize this effect. Switch cards are typically specified to operate in relative humidity of 50% or less.

One way to reduce leakage currents in the test fixturing is to use good quality insulators such as Teflon® and polyethylene. Avoid materials such as nylon and phenolics.

Another way to reduce leakage current due to cabling and test fixturing is to use guarding. By definition, a guard is a low impedance point in the circuit that is nearly at the same potential as the high impedance input terminal. **Figure 5-14** shows an example of guarding as applied to switching an ion chamber to an ammeter (pA) to measure the ion chamber current (I_x). An unguarded ion
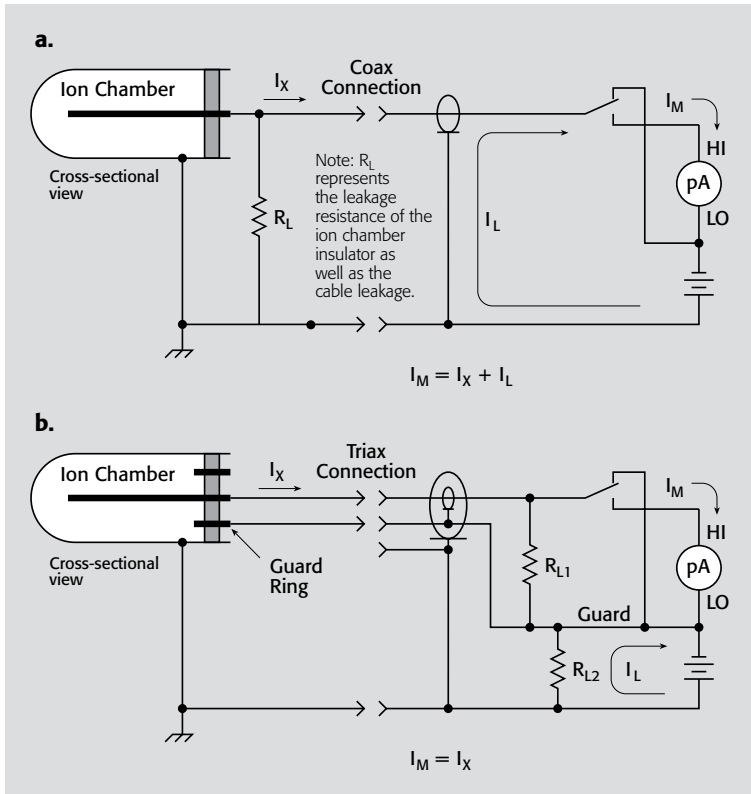
Figure 5-14. Guarding to reduce leakage currents when switching an ion chamber to a picoammeter

chamber is shown in **Figure 5-14a**. The circuit shows that the full bias voltage appears across the insulator leakage resistance (R_L), so a leakage current (I_L) will be added to the measured ion current ($I_M = I_X + I_L$). The leakage resistance (R_L) is due to the insulator of the ionization chamber and the coax cable insulation.

In **Figure 5-14b**, a guard ring is added to the ionization chamber. This guard circuit splits the leakage resistance into two parts. The coax connections of **Figure 5-14a** have been replaced with triax connections. The voltage across R_{L1} is the picoammeter voltage burden, normally less than 1mV, so the resulting leakage current will be quite small. The full bias voltage appears across R_{L2} (the leakage resistance between the inside and outer shields of a triax cable). However, the resulting leakage current does not flow through the meter, so it is not added to the measurement.

Guarding may also be necessary to prevent leakage current in low current test fixturing. Further information on guarding high impedance switching circuits is discussed in Section 5.4.2.

Electrostatic Interference

Shielding is required because high impedance circuitry is susceptible to pickup of spurious radiated noise. Relay contacts should be shielded from the coil to minimize induced noise from the relay power supply. The DUTs and interconnect cabling should also be shielded to prevent noise pickup. Any good conductor can be used as a shield. All shields should be connected to circuit LO.

Triboelectric Currents

Triboelectric currents are generated by charges created by friction between a conductor and an insulator, such as between the conductor and the insulation of a coax cable. This noise source can be reduced by using special low noise cable that has a conductive coating (such as graphite) and securing the interconnect cabling to minimize movement.

Electrochemical Currents

Electrochemical currents are generated by galvanic battery action caused by contamination and humidity. Thorough cleansing of joints and surfaces to remove electrolytic residue, including PC etchants, body salts, and processing chemicals, will minimize the effect of these parasitic batteries.

Settling Time

When a relay opens or closes, there is a charge transfer (on the order of picocoulombs), which causes a current pulse in the circuit. This charge transfer is due to the mechanical release or closure of the contacts, the contact-to-coil capacitance, and the stray capacitance between signal and relay drive lines. After a relay is closed, it's important to allow sufficient settling time before taking a measurement. This time can be as long as several seconds.

If a step voltage is applied to the circuit, a transient current is generated. This current will gradually decay to a steady value. The time needed to reach the steady value, or the settling time, can be used to determine the proper delay time for the measurement.

See Keithley's *Low Level Measurements Handbook* for more detailed discussions of generated currents and guarding.

5.3.3 Low Current Matrix Switching

Some low current applications require switching through a matrix. This is often the case when switching several Source-Measure Units (SMUs) to multipin devices or wafer level semiconductor measurements. All the special techniques used to minimize interferences for low current multiplexing also apply to low current matrix switching. These interferences and techniques were discussed in Section 5.3.2. However, offset current and leakage current are the types of interference most frequently encountered and are explained further at the end of this section. In general, low current matrix switching can become complex and is best explained by illustration.

Figure 5-15 shows three SMUs from the Model 4200-SCS Semiconductor Characterization System connected through a two-pole matrix (Model 7174A Low Current Matrix Card) to a multipin device. Notice that the FORCE terminal of each SMU is connected to the HI terminal of the switch and the Guard of the SMU is connected to the Guard terminal of the switch. In this example, guarding becomes important to avoid leakage currents because the FORCE terminal of the SMU is at the test potential. With the guard terminal at the same potential, the leakage current through the switch is minimized. Guarding will also speed up the response time. The ground terminal (GNDU) of the Model 4200-SCS is connected to a single row of the matrix.

Figure 5-16 shows two independent SMUs with the Output LO terminals connected to separate rows. Note that each pin of the device under test, the FET, is connected to a single column. The guard terminals of the matrix card are not connected to the device. To connect the SMUs to the transistor, close crosspoint Row 1/Column 2 to connect SMU1 to the drain, Row 3/Column 1 to connect SMU2 to the gate, and Row 2/Column 3 and Row 4/Column 3 to connect both SMU Output LO terminals to the source terminal of the FET.

Remote sensing may be necessary if the current through a given path is high enough to cause a significant voltage drop. Remote sensing compensates for test lead and switch voltage drops and ensures that the programmed output voltage of the SMU is delivered to the load. Remote sensing allows making accurate load voltage measurements. **Figure 5-17** shows SMU1 connected to four rows to enable remote sensing, thereby allowing accurate measurement of the collector-emitter voltage of the BJT. SMU2 is used to supply the relatively small base current and requires only two rows. To connect SMU1 between the emitter and the collector, close crosspoints Row 1/Column 4, Row 2/Column 5, Row 3/Column 2, and Row 4/Column 1. Note that remote sensing requires the use of four rows and four columns. To connect SMU2 between the base and the emitter, close crosspoints
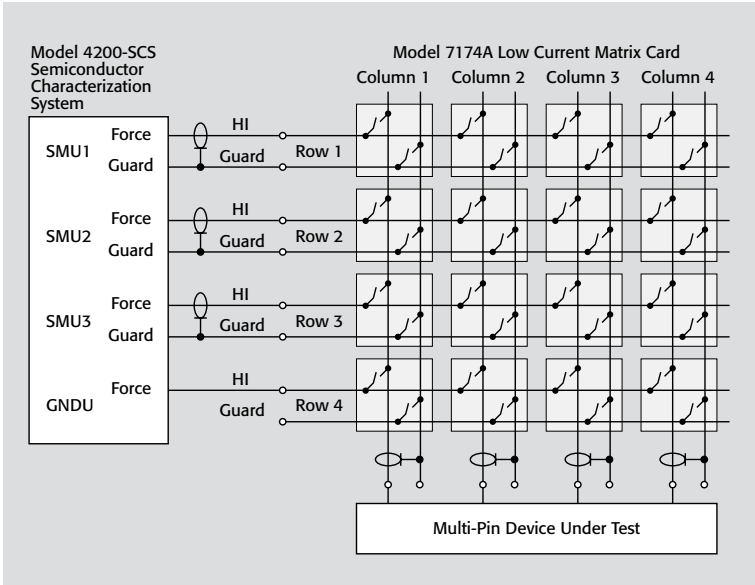
Figure 5-15. Using the Model 4200-SCS to test a multipin device
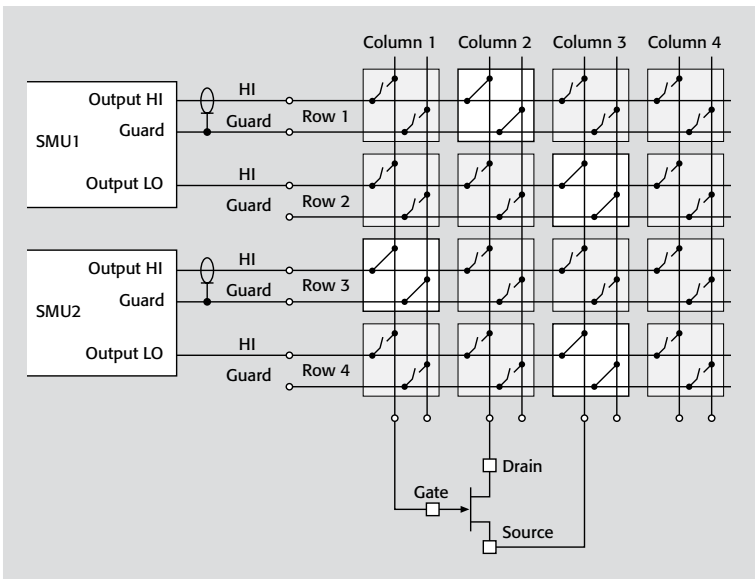
Figure 5-16. Using two SMUs to test a FET
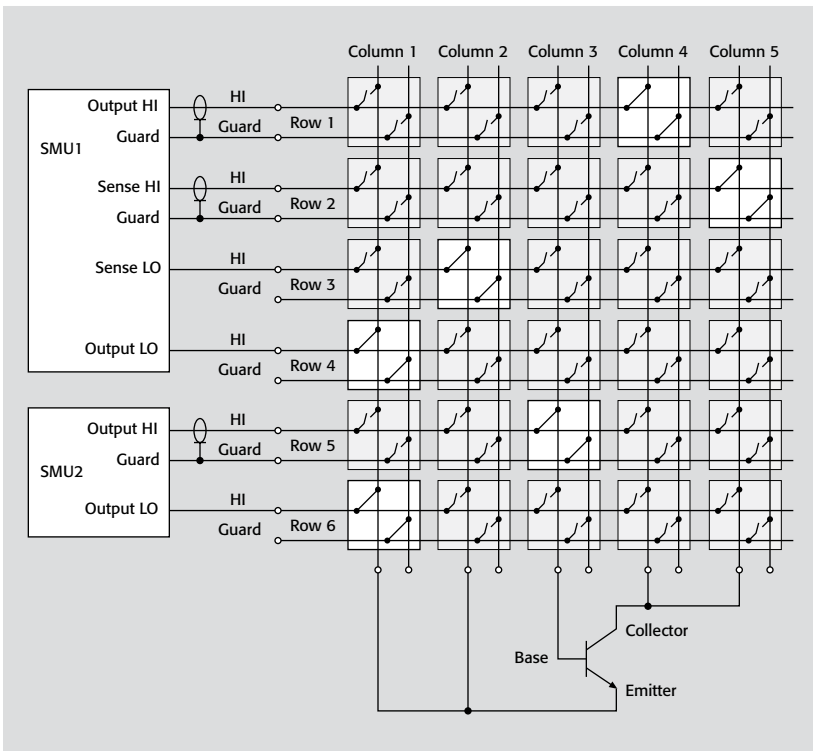
Figure 5-17. Using two SMUs to test a bipolar junction transistor (BJT)

Row 5/Column 3 and Row 6/Column 1. Remote sense is not needed to source the base current, because the lead resistance does not affect the current.

When connecting two SMUs in a matrix, the Output LO terminals of both SMUs can be tied together and connected to the device using one row. However, the SMU in remote sense may be outputting high current (>1mA) and the resulting voltage drop may interfere with the second SMU if it is used to measure small voltages (<1mV).

Once a given combination of matrix cards, sourcing, and measuring devices is put together, it may be desirable to measure the offset current for various pathways to characterize the system. To measure the offset current, close a specific cross-point and use an electrometer or SMU to measure the current with everything in place except the device under test. Periodically perform this system check on

only the crosspoints for low current switching. If the offset current is relatively constant, this value can then be subtracted from subsequent measurements.

Leakage current is another source of measurement interference that must be characterized. It is dependent on the applied voltage, contamination, and humidity. Leakage current can be determined from path to ground or from path to path. The leakage current can be determined by applying a known voltage and measuring the current between either path to ground or path to path. Once the leakage current in a given pathway is known and remains consistent, it can be subtracted from subsequent measurements. However, humidity and contamination may change the leakage current value over time, so it must be characterized periodically.

Matrix cards suitable for these applications include Models 7152, 7072, and 7174A. All connections should be made with triax cables. Low current matrix cards usually use triax connections to eliminate a possible shock hazard from the guard voltage. Note the outer shield is always at earth ground potential and has been omitted from these figures for clarity.
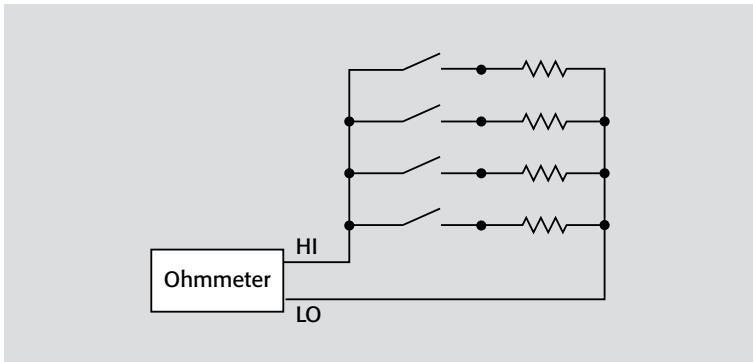
5.4 Resistance Switching

Switching an ohmmeter to a device under test is common to a variety of applications, including measuring the insulation resistance of materials, continuity testing of cables and connectors, contact resistance measurements, and measuring the resistance of components such as resistors, thermistors, and potentiometers.

Resistance measurements may range from less than 1Ω to greater than $10^{12}\Omega$, so the switching techniques required may vary significantly based on the magnitude of the resistance. Low resistance measurements are generally those less than 100Ω, mid-range are those from 100Ω to $10^7\Omega$, and high resistance measurements are those greater than $10^7\Omega$. As with any measurement, the exact point at which low resistance techniques should be used depends upon the desired measurement accuracy. For example, a 1ppm measurement of a $1k\Omega$ resistor implies an uncertainty of less than $1m\Omega$, which can only be achieved by using a four-wire technique. Separate sections describe low resistance (Section 5.4.1) and high resistance (Section 5.4.2) switching techniques. This section describes mid-range resistance techniques.

For scanning resistances in the mid-range (100Ω to $10M\Omega$), either single-ended (one-pole) or differential (two-pole) methods can be used. The single-ended method is shown in **Figure 5-18a**. Note that all the resistors under test have a common terminal that is connected to meter low.

Figure 5-18a. Single-ended resistance switching
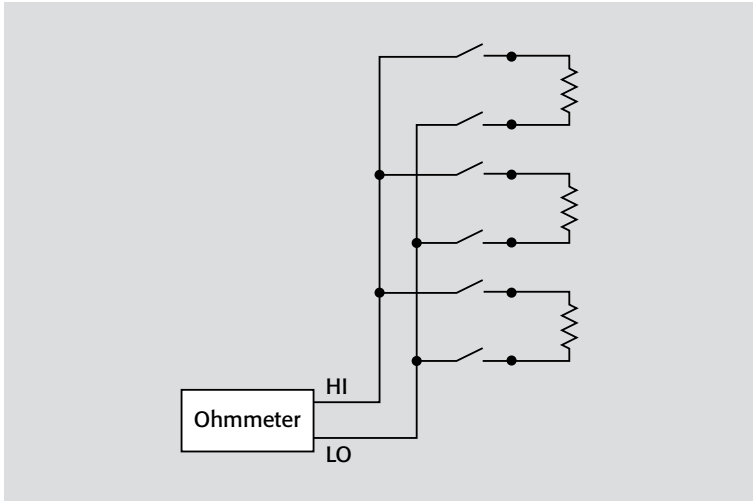
Figure 5-18b. Differential method for switching resistances

Figure 5-18b illustrates the differential method. A two-pole relay is used to connect both terminals of the unknown resistor to the meter.

The application usually dictates whether the single-ended or differential method should be used for switching. The advantage of the single-ended method is that it requires only half as many switches as the differential method. The only advantage of the differential method is that the offset voltages of the two switches tend to cancel each other. However, given that these are microvolt-level voltages, the differential method is not usually an issue for mid-range resistance switching.

5.4.1 Low Resistance Switching

Applications such as contact resistance measurements and cable continuity testing typically involve switching low resistances. Low resistance (<100Ω) switching requires using techniques that are normally unnecessary for mid-range or high resistances. Offset compensation and remote sensing are techniques often used to eliminate errors due to the switch contact resistance.

Offset Compensation

Spurious microvolt level signals are often present in low resistance circuits, most often as a result of thermoelectric effects. If dissimilar metals are present, a temperature differential across the circuit can easily add several microvolts to the measurement circuit. Switches in the circuit may also add up to several microvolts of error voltage to the measurement. This error voltage is known as contact potential or offset voltage.

Offset compensation will eliminate the switch contact potential, as well as any thermoelectric voltage offsets in the entire measurement circuit. Offset compensation requires making two voltage measurements with two different but known currents. Most often, the second current is of the same magnitude but opposite polarity as the first. The resistance is calculated by dividing the difference between these two voltage measurements by the difference between the two source currents. This procedure will cancel the offsets. In applications where timing is critical, offset compensation may not be practical, because it takes twice as long to make a measurement.

Some DMMs provide a built-in offset compensation capability. Two measurements are made, one at a positive current and another at nearly zero current. The DMM then calculates the resistance automatically.

Four-Wire Switching

Accurate measurements of low resistance in a system require a four-wire connection to eliminate both lead wire and switch contact resistance. **Figure 5-19** is an example of four-wire switching. In this diagram, two of the leads (HI and LO Source) supply current to the resistors, while the other two leads (HI and LO Sense) measure the voltage developed across the resistors. The source leads are connected to one bank of switches and the sense leads are connected to the other bank of switches.
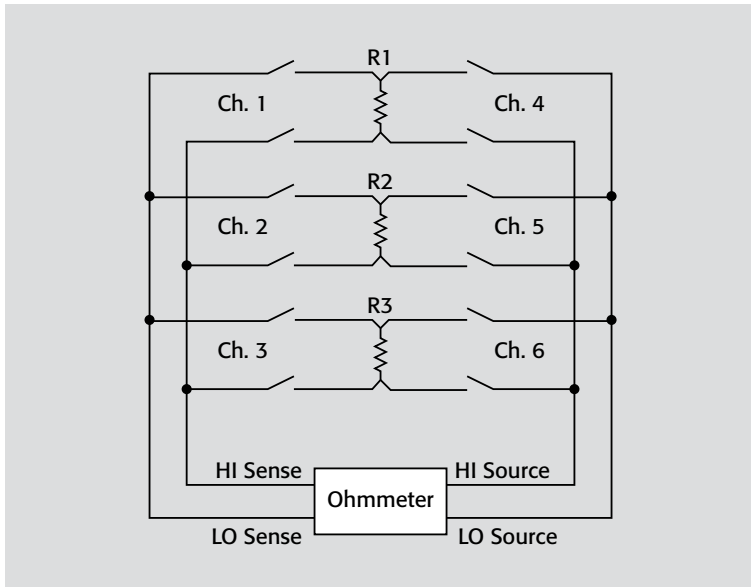
**Figure 5-19. Four-wire ohms scanning for measuring low resistances**

To measure the resistance of the first resistor (R1), channels 1 (Ch. 1) and 4 (Ch. 4) are both closed. The actual resistance measurement is made with either a DMM or a micro-ohmmeter with four-wire ohms capability, with a separate current source and voltmeter, or with a single source-measure instrument.

As shown in **Figure 5-19**, two sets of two-pole relays are used for low resistance switching. The poles in an individual relay will have similar offset voltages. By using these two poles to connect the low voltage signal to the sense terminals of the meter, the offset voltages or the contact potential (as it is specified), will tend to cancel each other. When the sense leads are connected through two different relays to the unknown resistor (R), as shown in **Figure 5-20a**, the offsets are not likely to cancel and may actually combine to cause an even greater error. Even a properly connected two-pole switch, like that shown in **Figure 5-20b**, will have some differential offset voltage that will not cancel out. The error caused by such offset voltage can be virtually eliminated by using offset compensation.

Figure 5-21 shows an example of the preferred connection scheme when testing metal-oxide varistors. The Model 2410-C SourceMeter® instrument is ideal for testing MOVs because of its ability to source up to 1100V at 21mA. One Model 7154 High Voltage Card connects the source lines to the devices and another Model 7154 connects the sense lines. The two-pole relays minimize lead resistance and
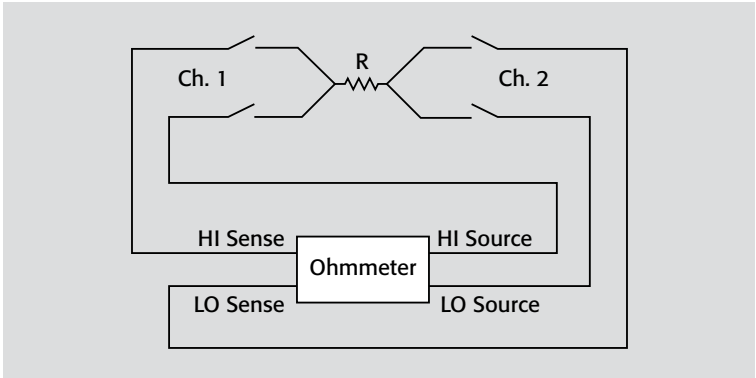
Figure 5-20a. Offset voltage of Ch. 1 and Ch. 2 will be added to sense voltage
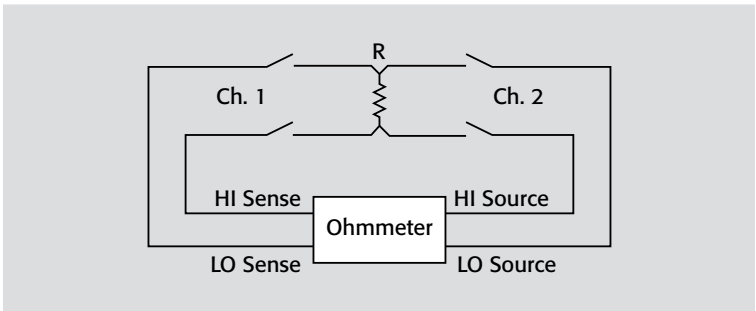
Figure 5-20b. Offset voltages of Ch. 1 will tend to cancel

voltage drop in the switch. This is particularly important when measuring relatively small voltages (millivolts).

On the other hand, the example of **Figure 5-22** minimizes lead resistance only. With the HI leads and LO leads on the same two-pole relays, offset voltages in the Model 3721 multiplexer switches will not cancel each other because very little current flows in the high impedance sense leads. Depending on the needs of the application, the offset voltages can be addressed with the offset-compensated ohms feature of the Series 2600 System SourceMeter instrument.

In some applications, the resistances to be tested may have a common terminal. In this case, only one two-pole switch per resistor is necessary, as shown in **Figure 5-23**. This approach has the advantage that only half as many switches are required, so it is more economical. The disadvantage is that the offset voltage of
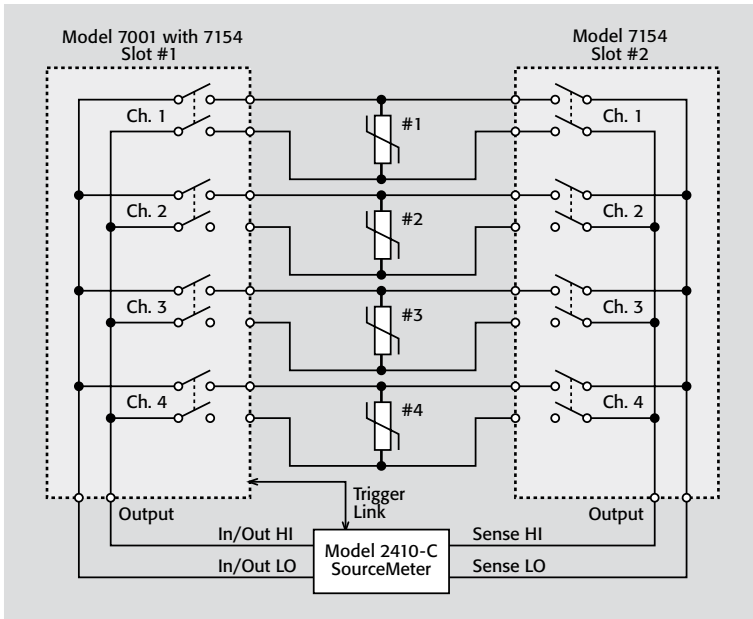
Figure 5-21. Switching multiple varistors
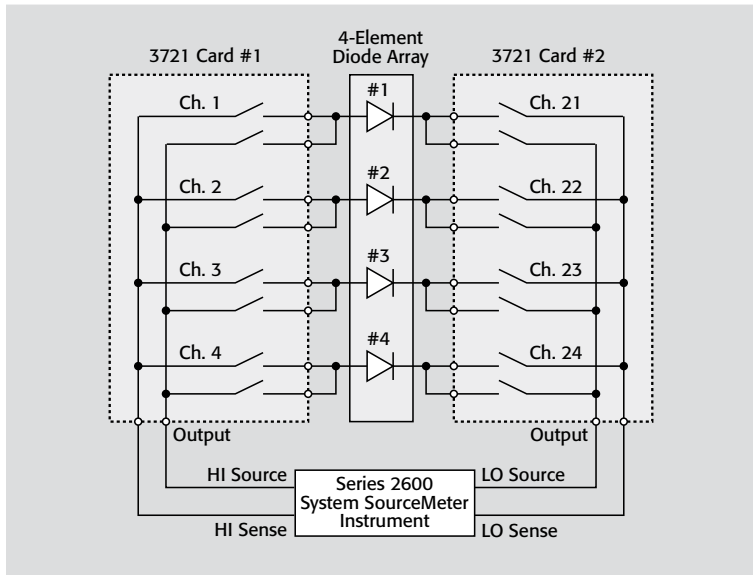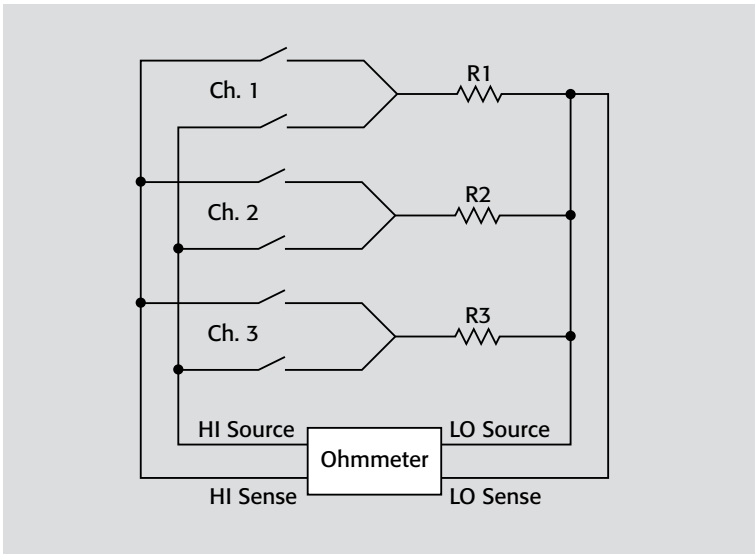

Figure 5-22. Switching multiple diodes

Figure 5-23. Four-wire resistance switching with common terminal

the single pole in the sense circuit is added to the measurement. Switching only a single sense lead will not cancel the offset voltage as happens when both sense leads are switched through the same two-pole relay. However, offset compensation will generally correct for this error source at the cost of increased measurement time. Some ohmmeters provide this feature, including two Keithley product configurations, the Model 2700 DMM/Switch Mainframe with the Model 7701 32-Channel Differential Multiplexer Card and the Model 3706 System Switch/DMM with the Model 3721 Dual 1×20 Multiplexer Card. This feature is known as "common side ohms." When operating in common side ohms mode, each instrument has the ability to recognize the appropriate card and convert the two-wire connection into a four-wire measurement.

Other Issues

Some low resistance applications may require sourcing a relatively high test current and measuring very low voltages. This may require using a high current switch card for sourcing and a low voltage switch card for measuring.

When switching low impedances, shielding needs are minimal. Shielding is generally needed only in electrically noisy environments.

More information on low resistance measurements can be found in Keithley's *Low Level Measurements Handbook*.

5.4.2 High Resistance Switching

Applications such as measuring capacitor leakage, multi-conductor cable insulation resistance, and pin-to-pin leakage of connectors require measuring high resistances through switches. Special techniques are required for switching resistances greater than 10MΩ. Different high resistance switching techniques will be needed, depending on whether the source voltage/measure current or the source current/measure voltage method of determining resistance is used. However, techniques such as shielding and guarding apply to both methods.

Source Voltage/Measure Current Method

This technique for measuring high resistance involves sourcing a known voltage, measuring the resulting current, and calculating the resistance. As shown in the schematic in **Figure 5-24**, one side of each resistor is connected through a set of switches to the picoammeter (pA), while the other end is connected through a second set of switches to a DC voltage source. To measure the resistance of R1, close switches Ch. 1 and Ch. 4.

If the measured current is less than 100nA, the switches used to connect the resistors to the picoammeter must have low offset current and high isolation resistance. In many cases, a Form C switch is preferred. The Form C switch keeps one end of the device under test at guard potential (approximately 0V) when the switch is de-energized. This prevents leakage current across the relay that would degrade the measurements. The Form C switch also allows the device under test to be charged for a controlled time interval before measuring.

General-purpose switches are usually sufficient for switching the voltage source unless high voltages (>100V) are involved, in which case, high voltage switch cards are necessary. If high voltage is used, current limiting resistors are needed to avoid damage to the current switches in case the device under test breaks down. The current limiting resistor (R) is placed in series with the device under test. The value of this resistor is chosen such that, in the event of device failure, the short circuit current will not exceed the maximum current specification of the relays on either set of switch cards. The voltage rating of these resistors must be at least equal to the test voltage.

In some cases, the device under test may have a common terminal, as shown in **Figure 5-25**. In this case, the voltage source will be applied to all the devices simultaneously. As a result, the excitation voltage time is different for each resistance to be measured. This will cause errors for some time-dependent applications, such as measuring insulation resistance or capacitor leakage. In these cases, the measured resistance is a function of the excitation time.
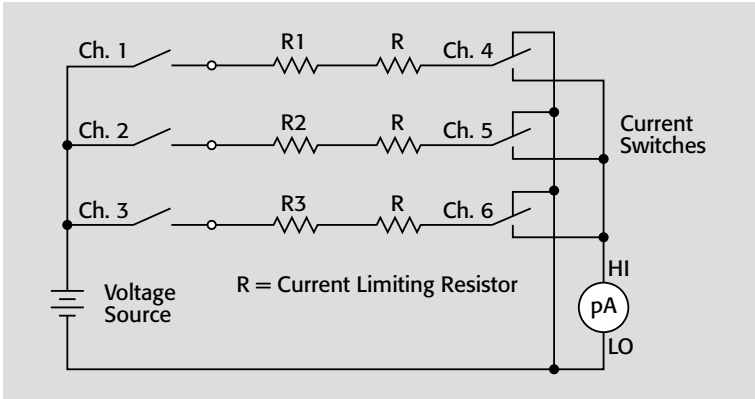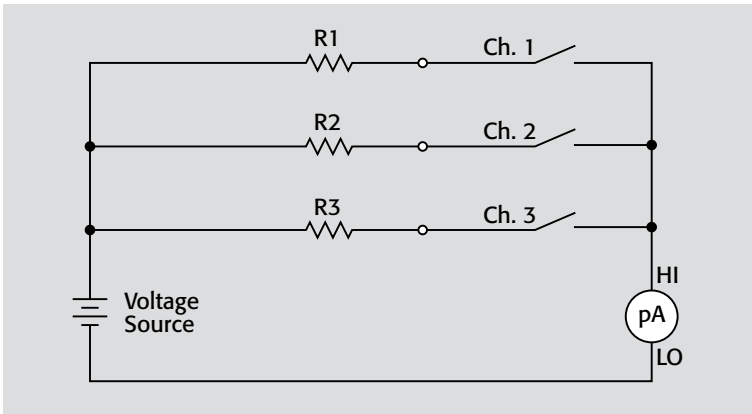
Figure 5-24. Switching high resistance
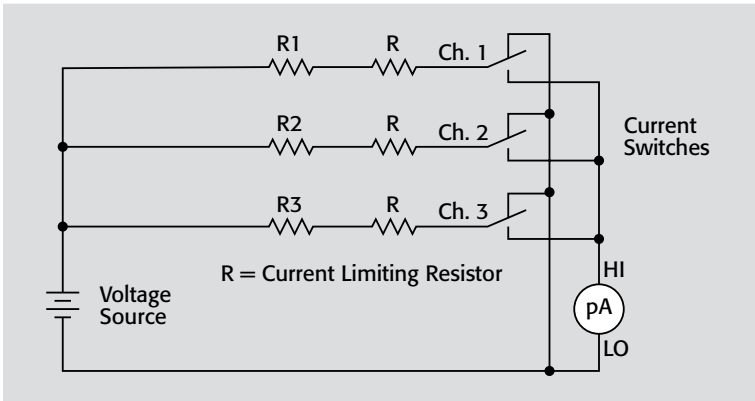
Figure 5-25. Switching high resistance with a common terminal

When the measured current is large compared to the relay current offset specification, then Form A switches can provide a more economical solution, as shown in **Figure 5-26**. In this example, the leakage current of all open relays will contribute to the measured current. Unfortunately, this leakage current cannot be guarded. Also, if there is a leakage path between devices (as when measuring the insulation resistance between traces on a circuit board or multi-conductor cable), this will also degrade measurement accuracy. In this diagram, each of the resistors has one end connected together to the voltage source. In this case, voltage source switching is unnecessary, because the device under test cannot be pre-charged.

Special techniques must be used to minimize interferences such as offset currents, leakage currents, electrostatic interference, triboelectric currents, and

Figure 5-26. Switching high resistances with common terminal and Form A switches
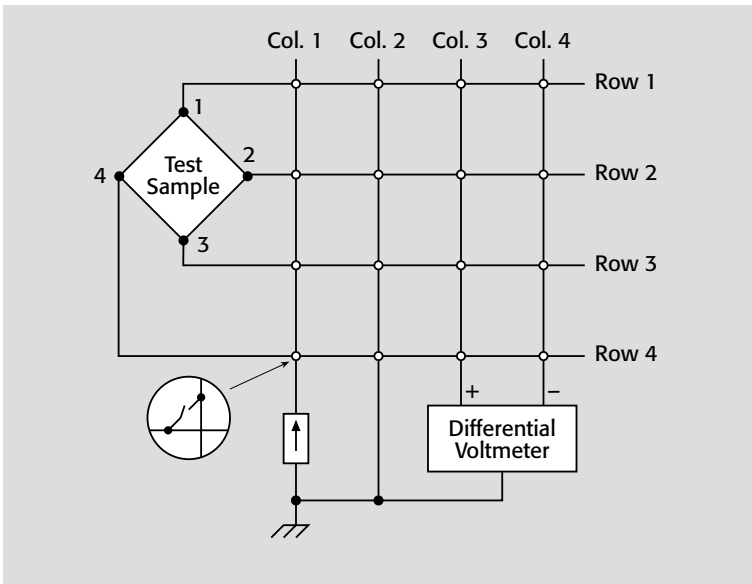
Figure 5-27. Van der Pauw resistivity measurements through a switch matrix

electrochemical currents. These sources of errors may be due to the switch card or the connecting test fixturing. These interferences and ways to avoid or mini-mize them are discussed in detail in Section 5.3.1.

Source Current/Measure Voltage Method

In some cases, high resistance is measured by sourcing a current and measuring the resulting voltage. Although this is not the preferred method for measuring high resistance, it is necessary for some applications, such as van der Pauw resistivity measurements of semiconductors. High impedances are being switched, so some of the same switching techniques used when switching low current (Section 5.3.1) and high impedance voltages (Section 5.2.3) are equally applicable here. To avoid errors, choose a card with low offset current and high isolation resistance. Shielding is necessary to prevent noise due to electrostatic interference.

Figure 5-27 shows a simplified van der Pauw resistivity measurement with a current source and a differential voltmeter. By closing crosspoints Row 1/Column 1 and Row 2/Column 2, the current source is connected to sample terminals 1 and 2. Closing crosspoints Row 3/Column 3 and Row 4/Column 4 will connect the voltmeter between terminals 3 and 4. For more detailed information on van der Pauw resistivity measurements, consult Keithley's *Low Level Measurements Handbook*.
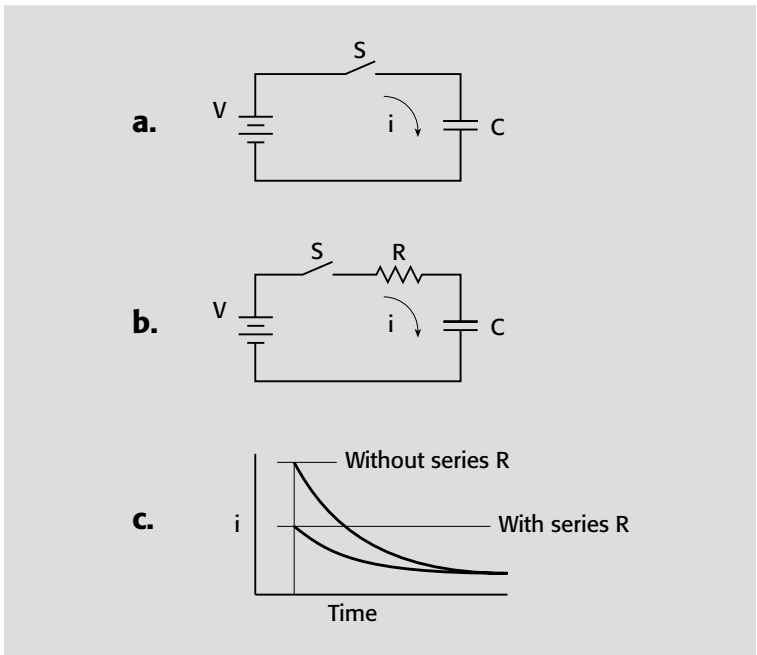
Figure 5-28. In-rush current of capacitive load

5.5 Signals Involving Reactive Loads

Switching circuits that include reactive elements need special care to avoid problems due to transient effects. The methods used to limit transient effects depend on whether the load is capacitive or inductive.

When a capacitive load is connected through a switch to a voltage source, the in-rush current may exceed the current rating of the switch and weld the contacts shut. As **Figure 5-28a** indicates, when the switch (S) is closed, the peak current (i) is limited mainly by the sum of the wiring resistance and the relay contact resistance. The peak current may exceed the current rating of the relay and cause welding of the contacts. Cold switching is the most effective way to prevent this

a. Varistor Clamped (AC or DC Voltages)

b. Diode Clamped (DC Voltages)

c. Zener Clamped (AC Voltages)

d. Resistor-Capacitor Clamped (AC Voltages)
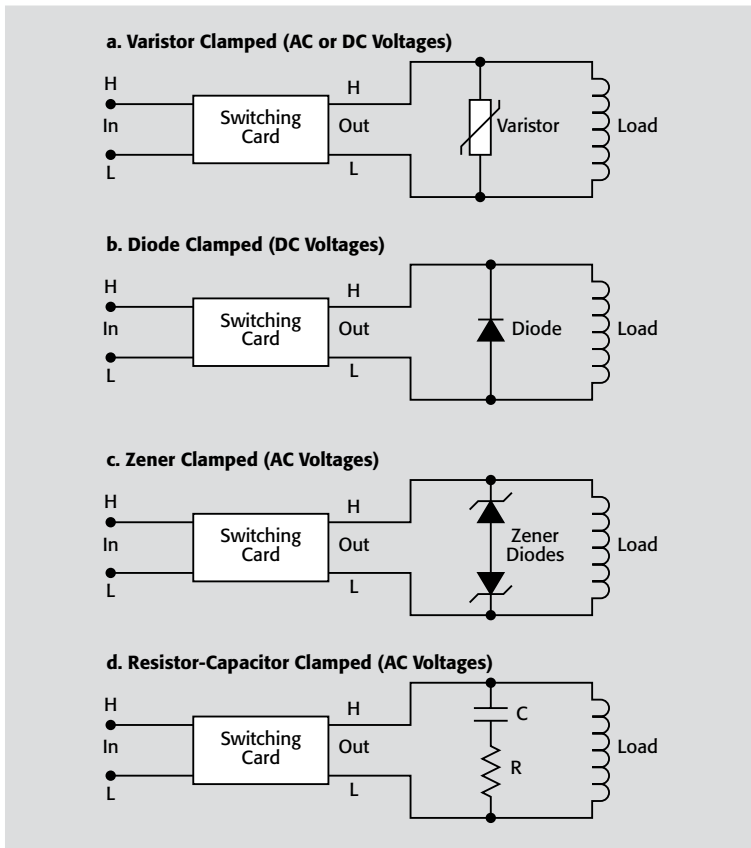
Figure 5-29. Limiting inductive reaction load

current surge. If cold switching is impractical, it may be possible to add series resistors to limit the current to a safe value, as shown in **Figure 5-28b**. The value of the series resistor (R) should be greater than the ratio of the applied voltage to the maximum current rating of the switch card. However, if the resistor is too large, it may affect measurement accuracy. The current surges of these two circuits are illustrated in **Figure 5-28c**.

Capacitor leakage measurements and insulation resistance measurements of multi-conductor cables are two applications where switching capacitive loads may be a particular problem. Even with resistive loads, the capacitance of a shielded connecting cable may cause relay welding. In this case, the series resistor should be placed as close to the relay as possible to limit the current when charging the cable capacitance.

When an inductive load is connected to a voltage source, the current will increase relatively slowly. However, when the switch is opened, a large inductive reaction voltage will appear across the switch contacts and may damage the contacts. The contact bounce that occurs on closure can also produce an inductive reaction voltage, because the current is interrupted repeatedly. A voltage-clamping device across the inductive load is usually required. **Figure 5-29** illustrates four possible circuits for voltage clamping. For best results, the voltage-clamping device should be located near the load.

Applications that involve switching inductive loads include testing motors, solenoids, and transformers.

5.6   RF and Microwave Switching

Given the explosive growth of the communications industry, a tremendous amount of testing is being performed on the various components that make up different communications systems. These components range from active components such as Radio Frequency Integrated Circuits (RFICs) and Microwave Monolithic Integrated Circuits (MMICs) to complete communication systems. While the testing requirements and procedures for these components differ widely, all are tested at very high frequencies, typically in the gigahertz range. The main components in a test system may include DC bias, DC measurement, RF power meter, network analyzer, RF sources, and other instruments. Automating the test process and improving test efficiency demands integrating RF/microwave and low frequency switching systems into the test system.

This section describes microwave switch types, RF switch card specifications, and RF switch design considerations.

Microwave Switch Types

Available microwave switch configurations include a simple single-pole double throw (SPDT) switch, multi-position switch, matrix, and cascade.

An *SPDT switch* has one input port, which can be connected to one of two output ports. A *multi-position switch* connects one input port to one of several output ports. Keithley's System 46 can accommodate eight SPDT coaxial microwave relays and four multi-pole coaxial microwave relays.

A *matrix switch* can connect any input to any output. Two types of matrices are used in microwave switching: blocking and non-blocking. A blocking matrix connects any one input to any one output. Other inputs and outputs cannot be connected at the same time. A non-blocking matrix allows multiple paths to be connected simultaneously through the matrix.

The *cascade switch* configuration is an alternate form of multi-position switch. The cascade switch connects one input to one of many outputs using multiple relays. The path length (and therefore, the phase delay) varies, depending on the number of relays that the signal must go through.

More detailed information on the cascade, tree, and matrix switching configurations, including diagrams, can be found in Section 1.4.5.

RF Switch Card Specifications

The use of a switch will inevitably degrade the performance of the measurement system, so it is important to consider several critical parameters that may affect system performance significantly. During the design phase, the costs and benefits are often weighed against each other to achieve an optimal solution.

When choosing an RF switch system, some of the critical electrical specifications to review include crosstalk (path isolation), insertion loss, voltage standing wave ratio (VSWR), and bandwidth. These specifications are defined and discussed in Sections 3.2.10, 3.2.11, 3.2.12, and 3.2.13 respectively.

RF Switch Design Considerations

When designing an RF switch system, additional factors that may affect switch system performance include impedance matching, termination, power transmission, signal filters, phase distortion, and cabling.

Impedance Matching: Given that the switch is positioned between the measurement instruments and the DUT, matching the impedance levels of all elements in the system is critical. For optimal signal transfer, the output impedance of the source should be equal to the characteristic impedance of the switch, the cables,

and the DUT. In RF testing, the most commonly used impedance levels are 50Ω and 75Ω. Whichever impedance level is required, proper matching will ensure the overall system integrity.

The input VSWR and signal path VSWR determine the limitation on the accuracy of the measurement:

Mismatch Uncertainty (dB) = $20 \times \log (1 \pm \Gamma_{\text{sig path}} \Gamma_{\text{instr}})$

where $\Gamma = \dfrac{\text{VSWR} - 1}{\text{VSWR} + 1}$

If both the signal path output and the instrument input have good VSWRs of 1.3:1 at a frequency, then the uncertainty due to mismatch alone is ±0.15dB.

Termination: At high frequencies, all signals must be properly terminated or the electromagnetic wave will be reflected from the terminating point. This, in turn, will cause an increase in VSWR. An unterminated switch increases VSWR in its off condition, while a terminated switch will try to provide a 50Ω match on or off. The VSWR increase may even damage the source if the reflected power is large enough. All paths through a system must be terminated with their characteristic impedance.

Power Transmission: Another important consideration is the system's ability to transfer the RF power from instrument to DUT. Due to insertion loss, the signal may require amplification. In other applications, it may be necessary to reduce the signal power to the DUT. An amplifier or attenuator may be needed to ensure that the required level of power is transmitted through the switch.

Signal Filter: Signal filters can be useful in a number of circumstances, such as when spurious noise is inadvertently added to the signal as it travels through the switch. They can also be helpful if the original signal frequency does not fit in the DUT testing frequency. In these cases, filters can be added to the switch to modify the signal frequency bandwidth, or spurious signals at unwanted frequencies can be eliminated from the signal to the DUT.

Phase Distortion: As the size of a test system expands, signals from the same source may travel to the DUT via paths of different lengths, resulting in phase distortion. This specification is often referred to as propagation delay. For a given conducting medium, the delay is proportional to the length of the signal path. Different signal path lengths will cause the signal phase to shift. This phase shift may cause erroneous measurement results. To minimize phase distortion, keep the path lengths the same.

Taking all of these design considerations into account when configuring an RF/microwave switch system can be simplified by ordering a package solution, such as the System 46 RF/Microwave Switch System. It can be configured with up to 32 channels for controlling microwave switches. It also tracks contact closures for proactive maintenance of relays, and performance parameters, such as VSWR or insertion loss, for trend analysis.

5.7   Digital Switching

High speed digital signals exhibit RF behavior in real-world devices, which creates a need for RF or microwave components when routing these signals in test systems. Digital (and optical) engineers must be aware of RF parameters in product development and production testing.

Digital Design Considerations

The first consideration when switching digital signals is providing adequate bandwidth to preserve the frequency harmonics of the digital pulse and their power spectral distribution. The switching solution should have as a minimum the bandwidth of the DUT, and preferably equal to the bandwidth of any higher frequency source and measurement equipment.

Since the –3dB specifications of switch cards are based on sinewave signals, an approximation is needed for square waves. If the frequency of the square wave is known, the required bandwidth is determined by the highest harmonic that needs to pass without distortion, whether that is the third, fifth, seventh, or higher harmonic.

If the frequency of the square wave is unknown, the following equation approximates the minimum bandwidth for digital signals:

$$\text{Bandwidth (Hz)} = \frac{0.35}{\text{risetime (s)}}$$

Digital switching has some other considerations in addition to those listed in Section 5.6:

Arcing: The RFI (radio frequency interference) generated by high voltage switching may disrupt high-speed logic circuits.

Hot switching: When digital signals are being switched, they may change state with any length of power interruption. Using hot switching prevents digital state changes.

Make-before-break: Use Form A isolated switches instead of Form C relays to allow for make-before-break operation.

SECTION 6

Hardware Implementation

6.1   Introduction

Section 6 describes ways to implement and test the switching hardware. This section addresses connections, wiring and cabling, shielding and grounding, hardware verification, and troubleshooting. Refer to the user's manual for the switching hardware for further information on these subjects.

Under no circumstances should unlimited power (direct from the power line) ever be connected directly to a switch card.

6.2   Connections, Wiring, and Cabling

Before attempting to wire the system together, create an accurate wiring diagram for the entire system. Information about making connections to a particular switch card can be found in the card's manual.

The types of connectors and cables used in the system depend on the types of switch cards used and the signals being switched. In general, there are four types of connections on switch cards: screw terminals, mass-terminated connectors, coax connectors, and triax connectors.

For screw terminal connections, use individually insulated wires. Make sure the wires are long enough so that the switch cards can be removed easily from the mainframe for service. Ribbon cable is convenient, because it keeps the wires neatly organized and mass-terminated connectors for it are readily available. However, the conductors in the ribbon cable are not individually shielded, so there may be excessive stray coupling between conductors, which may interfere with measurements. If that is the case, individually shielded conductors are necessary.

Twisted-pair conductors are sufficient if frequencies of interest are below a few hundred kilohertz. Thin-diameter wires of 22 to 26 gauge are twisted around each other to minimize interference. Cables with twisted pairs are available shielded or unshielded. Stranded wire is more common than solid wire and is more flexible, but solid wire has less attenuation.

If mass-terminated cables are used, mating receptacles can be mounted at the test fixture. This requires a cable with mass-terminated connectors on both ends. However, it may be more economical to cut mass-terminated cables in half and hardwire the individual wires to the test fixture.

The same is true with systems that employ coax or triax cables. The simplest approach is to use cables with connectors at both ends. A receptacle for each signal is mounted at the test fixture, and the cables are used to connect them to

the switch cards. Again, it may be more economical to cut the cables in half, then permanently connect the cut ends to the test fixture. Keithley's *Low Level Measurements Handbook* provides more information about using coaxial and triaxial cables and connectors, including low-noise cables, and cable and connector assembly.

To connect the outputs of the cards together, certain cards have their outputs connected to the backplane of the scanner mainframe. This allows the outputs from one card to be connected to the other cards in the mainframe. For some switch cards compatible with Keithley's Models 7001 and 7002 mainframes, jumpers on the switch cards enable connection or disconnection from the backplane. If one card must be isolated from the others, the backplane jumpers on that card must be removed. The switch modules for the Models 2700 and 2750 include isolation relays that allow the outputs to be connected or disconnected from the backplane. The Series 3700 switch modules have up to six backplanes (known as ABUS1–ABUS6) with relays on each to attain maximum flexibility and isolation. Some matrix cards of the Models 707A and 708A make connection to the backplane through jumpers on the cards, while other cards that are optimized for low current switching use external low noise jumpers.

In some applications, it is undesirable to connect a card output to the backplane, so always check the schematics of the individual cards before applying power to ensure backplane connections are not made by default. When the output of a card must be isolated from the backplane, make connections to the output directly to the card.

RF/Microwave Connectors and Cables

Many different types of connectors and cables can be used in RF and microwave switch systems. The signal frequency, the system impedance, power rating, and test fixture/handler compatibility, etc. should all be taken into consideration when choosing cables and connectors. For example, a typical SMA connector can handle 500 watts at 100MHz but very little power at 26.5GHz.

BNC connectors are commonly used on both 50Ω and 75Ω systems. At frequencies lower than microwave frequencies, users often have a variety of connectors on their peripheral equipment and/or DUT. In these cases, coaxial connector adapters may be applicable, providing they offer proper performance and impedance matching. The connector size (diameter) should match the cable outer diameter as closely as possible to minimize reflections.

Table 6-1 shows some common RF/microwave connectors. The frequency limits of the connectors vary by manufacturer and grade (general purpose grade for

limited connections and low repeatability, or instrument grade for repeated connections and high repeatability).

Table 6-1. Common RF/Microwave Connectors

Connector Type	Typical Frequency Limit (GHz)	Characteristic Impedance (ohms)	Dielectric	Coupling
BNC	2.4 or 4	50 or 75	Teflon® PTFE	bayonet
SMB	4	50 or 75	Teflon® PTFE	push-on
N	11 or 18	50 or 75	Teflon® PTFE	threaded
SMA	18 or 26.5	50	Teflon® PTFE	threaded
3.5mm	26.5 or 34	50	air	threaded, mates with SMA*
2.92mm	40	50	air	threaded, mates with SMA*

*See discussion of RF/microwave connector mating.

The connector designations of 3.5mm and 2.92mm refer to the inside diameter of the connector's outer conductor. With these small connectors, air is used as a dielectric material, since it is less of a variable than the thickness of Teflon in SMA connectors, for example. This provides for a more repeatable connection with better electrical performance. Of course, connector cost increases with the frequency limit because of tighter manufacturing tolerances.

With the use of electromechanical switches, it becomes necessary to use RF coaxial cable to route the signal path throughout the test system with minimal losses. Coaxial cable should provide low insertion loss, low VSWR, and proper RF shielding with the appropriate connectors on the ends of the cable assembly. Insertion loss is perhaps the parameter of greatest concern when using coaxial cable, and given that this specification increases proportionally with length, it is desirable to *use the shortest length cables* available for the application. **Table 6-2** lists VSWR and insertion losses for various frequency ranges for a 10-inch SMA cable.

Table 6-2. SMA Cable (10-inch, 0.141-inch diameter)

Frequency Range (GHz)	DC – 1	1 – 2	2 – 4	4 – 6	6 – 12	12 - 18
VSWR (max.)	1.06:1	1.10:1	1.14:1	1.17:1	1.20:1	1.30:1
Insertion Loss (max. dB)	0.17	0.23	0.34	0.42	0.62	0.82

Generally, larger diameter cables offer lower insertion loss and higher power handling capability, but decreased bandwidth and flexibility when compared to smaller diameter cables.

Some applications require phase-matched cables. This specification typically calls for a certain degree of phase tolerance between two or more cables at a stated frequency (e.g., 5° phase matching at 10GHz means the phase difference between signals through any cables in that particular set should be no greater than 5° at 10GHz). A typical phase match specification is ±1°/GHz for semi-rigid cables and ±2°/GHz for flexible cables.

Phase delay is also related to time delay; therefore, the specification may be given as time delay (nanoseconds of delay per foot of cable) instead of phase delay. Phase matching is of particular concern with some high speed digital circuits, because unmatched cables may cause excessive clock skew, resulting in erroneous operation.

Note that at higher frequencies, the physical length of a cable is different from its electrical length. Phase-matched cables are not produced by cutting the cables as equal in length as possible, but by measuring the time delay along the cables. Cables purchased in a phase-matched set should be clearly labeled and used as a set.

RF/Microwave Connector Mating

Mating connectors must be clean, must meet connector type interface, and must be tightened to the appropriate torque specification. Mating connectors with out of tolerance pin depths may destroy the connector. Verify pin depth before mating connectors.

Misalignment of the outer and inner conductors is impossible to avoid when different connectors are mated. Since misalignment degrades electrical performance, mating different types of connectors should be avoided.

To mate a test cable to a test system connector:

- Remove power from the test system.

- Remove the protective caps from the connectors and save for future use. Keep caps on all unused connectors.

- Connect the test cable and tighten to specified torque with a torque wrench.

RF/Microwave Connector Cleaning

To prevent performance degradation, RF and microwave connectors must be free of foreign materials. Visually inspect connectors using a 4× to 10× magnifying glass. Try to blow off foreign material off the connector using canned air (canned

air is recommended due to the presence of moisture and oils in air supplied by standard industrial compressors). Use a lint-free miniature cleaning swab moistened with clean isopropyl alcohol to wipe off any remaining foreign material.

Optical Cables and Connectors

Optical fiber has several advantages over copper wiring, including less susceptibility to interference, less attenuation, and greater bandwidth.

An optical fiber consists of a fiber core surrounded by a cladding layer surrounded by a protective coating. The most popular type of fiber optic cable has a glass core and glass cladding. Plastic cores and cladding are also available, but with their greater attenuation they are not used for telecommunications.

The glass fiber core comes in one of two basic types: multimode fiber for distances up to 10km and single-mode fiber for longer distances. The core diameters of multimode fiber (MMF) typically range from 50 to 62.5μm. For single-mode fiber (SMF), core diameters are typically 8 to 10μm. Cable sizes are usually expressed with the core size followed by the cladding size. Size 9/125 is often used for single-mode fiber, and size 62.5/125 is often used for multimode fiber.

Optical connectors come in many varieties, depending on the type of fiber (glass or plastic), repeatability of connections, and vibration resistance. A common connector for single-mode and multimode cables is the FC connector. This connector features a position locatable notch and a threaded receptacle. The insertion loss for matched FC connectors is typically 0.25–0.5dB.

6.3 Shielding and Grounding

Electrostatic shielding may be necessary to prevent interference with a desired signal. In particular, shielding is necessary with high impedance circuits, high frequency circuits, and with mixed signal applications where high voltage signals may be inadvertently coupled to low level signals. Shielding is not usually necessary when switching low impedance signals, such as 100Ω or less.

Switching applications of high impedance circuits include low current, high resistance, and high impedance voltage applications. High impedance is best defined as the level at which interferences cause significant errors. Without proper shielding of the switches, interconnecting cables, and test fixturing, spurious signals (offsets) may be generated that will compromise the signal being measured.

Electrostatic shielding is provided by surrounding the signal path with a conductor connected to a low impedance point in the circuit, preferably the

LO input terminal of the measuring device. If there is no measuring device in the circuit, then the shield should be connected to the LO output terminal of the source.

To ensure proper shielding, choose a switch card with shielded connectors, such as coax or triax connectors. Switch cards with coax or triax connectors are inherently shielded and will generally provide good isolation from channel to channel. Cards with screw terminals or mass-terminated connectors are not as well shielded, so they are generally not useful for switching high impedance circuits.

Also, shielded cabling, such as coax or triax, should be used to make connections from the high impedance devices or signal sources to the switch card. The high impedance devices and signal sources must also be shielded. The degree of shielding required will depend upon the amount of interference in the environment. Motors, solenoids, and other devices may generate high voltage transients, and better shielding will be required.

Further information on shielding low current, high resistance, and high impedance voltage circuits can be found in Section 5.

Shielded cable for high frequency (>1MHz) test signals is also necessary to maintain the characteristic impedance and to prevent signal loss and unwanted coupling (or crosstalk) with adjacent circuits, which may affect the measurement accuracy. Use the appropriate impedance coax cables, and completely shield the test fixture to prevent leakage of high level signals. All shields should be connected to an appropriate ground plane. See Section 5.6 for further information on RF and microwave switching.

Shielding may be essential in a switching system if a mixture of low current, high voltage, and high frequency signals are present. With most switch cards, there will be some small capacitance between adjacent channels. Voltage present on one channel can easily be coupled to an adjacent channel and may cause significant errors. This can be minimized by locating the high voltage channels away from the sensitive low current channels and by using well-shielded switches.

Shielding may also be applied to a conductor carrying a high level test voltage to prevent interference with nearby low level circuits. Coaxial cable is most often used for this purpose.

Grounding, in the true sense of the word, means making a connection to earth (ground). The primary purpose of this connection is to ensure personal safety for the equipment operator. The signal return path is often considered ground

and is often referred to as "common" or "LO." It may or may not be connected to earth ground.

Shields are often "grounded," that is, they are connected to an earth ground point. If the return side of the signal source or the measuring device is connected to this same point, there will be a minimum of interference. If there is an AC potential difference between the shield and the measuring instrument, there may be capacitive currents flowing through the measuring circuit that will add interference.

In general, only one point in the measurement system should be connected to earth ground to avoid ground loops.

6.4 Hardware Verification and Troubleshooting

Once the switches, instruments, and test fixtures are wired together, the performance of the system must be verified. This is usually done in two steps: first manually through the front panel controls, then as a system under computer control. The specific verification procedure used will depend upon the type of signals being switched and the type of measurements to be made. Examples are provided for resistance, voltage, and current measurements.

Resistance Measurements

The first step to verify the system requires that resistors of known value be placed in the test fixture. An example might be a system for testing resistor networks. The individual resistor values should be similar but not identical to make certain that the proper connections are made to each element. For instance, if the nominal resistances are all 10kΩ, then a suitable test device could have 10.1kΩ on Channel 1, 10.2kΩ for Channel 2, etc. In this way, if one or more channels are incorrectly wired, it will be obvious immediately.

If the range of resistance values to be tested is very wide, then tests must be made with known resistors near both the maximum and minimum limits. If the system makes two-terminal connections to the devices, a measurement near the minimum value may have excessive error, indicating the need for four-terminal connections. This will require twice as many switches, but it will eliminate the switch and lead wire resistances from the measurement.

At the maximum limit, a lower than expected measurement would indicate excessive leakage resistance in the test fixture, the wiring, or the switch cards, and appropriate steps must be taken to reduce this error to an acceptable level.

These steps include cleaning the test fixture and adding electrical guarding. See Section 5.3.2 for details on guarding.

Particularly for high resistance measurements, the system settling time should be verified as sufficient to provide the desired accuracy.

Voltage Measurements

For voltage measurements, first verify that each voltage source is connected to the correct channel. The straightforward way to make sure the channels are connected properly is to connect known voltages on each channel. For example, apply 1V to Channel 1, 2V to Channel 2, etc.

To make certain that voltage offsets are not contributing excessive error to low voltage (<1mV) measurements, first take a series of readings with a known stable source connected directly to the voltmeter. Then, take another series of measurements of the same source through a given channel of the switch system. Compare the standard deviations from the two tests. Excessive voltage offsets can be compensated for on each channel by replacing the voltage signal with a short circuit using a clean copper wire. For each short-circuited channel, take at least ten voltage readings and average them. Save the average value, and use this to correct future measurements made on that channel. For this to be effective, the ambient temperature of the switch system must remain relatively constant (plus or minus a few degrees Celsius).

If this procedure is too cumbersome, then use the following method: Connect a short-circuit to only one channel, then use the offset of that channel to correct measurements made on all other channels of the card.

If the source resistance is very high (1MΩ or higher), serious errors can occur if there is significant leakage in the system. To determine if this is the case, first measure a low impedance voltage source through the channel. Then add series impedance that is comparable to that of the unknown sources to the low impedance source and repeat the measurement. Compare the results. If there is a large difference, check for possible causes such as cable leakage or switch isolation resistance. Guarding may help reduce errors in the measurement. It may be necessary to increase settling time delays when high source resistances are involved.

Current Measurements

For current measurement verification, first ensure that the path for each unknown is complete from the test fixturing to the ammeter. If using a switch card with Form C switches (SPDT), this can be done by connecting an ohmmeter in place

of the unknown source on each channel. Verify that this path resistance is low when the channel is not selected, typically less than 1Ω.

The next step is to connect a known source of current to each channel one at a time, and verify that the output is within overall system accuracy limits.

For low current measurements, the switch card, cables, and test fixturing may introduce significant offset current. To check the offset current for each channel, disconnect the unknown source, cap the input, then activate each channel one at a time and measure the offset current with the ammeter connected to the output. If the offset current is too high, it may be necessary to clean the switches and connectors in the pathway. (Refer to the switch card's manual.) If the offset current is reasonably stable, it can be compensated for by subtracting it from future measurements.

Also, for low current switching, provide sufficient settling time after each relay actuation to ensure accurate results.

Final System Verification

Once the system has been completely checked out manually, verify the performance again under computer control. This will reveal any possible errors in the software, such as incorrect switch closures or device address errors, as well as timing problems, excessive crosstalk, etc.

As a final test, run a significant quantity of product through the system, then manually retest all the rejected components, as well as a fraction of the good components to verify system performance.

At this point, the system can be considered ready for service. Periodically, the system should be tested using known good devices to ensure the system has not drifted out of specification.

SECTION 7

Applications

7.1   Battery Testing

Batteries are used in a rapidly expanding variety of consumer and industrial applications. Their testing requirements typically depend on their chemistry, size, specific use, and whether the cells are primary or secondary.

Secondary (rechargeable) batteries are commonly tested using discharge and charge cycling. The discharge characteristics of a secondary battery provide important information about the battery's capacity and life. Charging/discharging a battery often takes several hours, so it is usually desirable to connect several batteries in series in order to charge and discharge them simultaneously. The voltage of each battery can be monitored during charging and discharging using a two-pole scanner.

In some applications, it may be desirable to measure each cell voltage, both with and without a load. Monitoring the voltage decay over time will give an indication of cell quality. While this is particularly true for primary cells, this technique can also be used for secondary cells. Using a scanner makes it possible to monitor the voltage decay of several cells at one time.

The following paragraphs describe the switch configurations for both the charge/discharge cycling test and the voltage monitoring test.
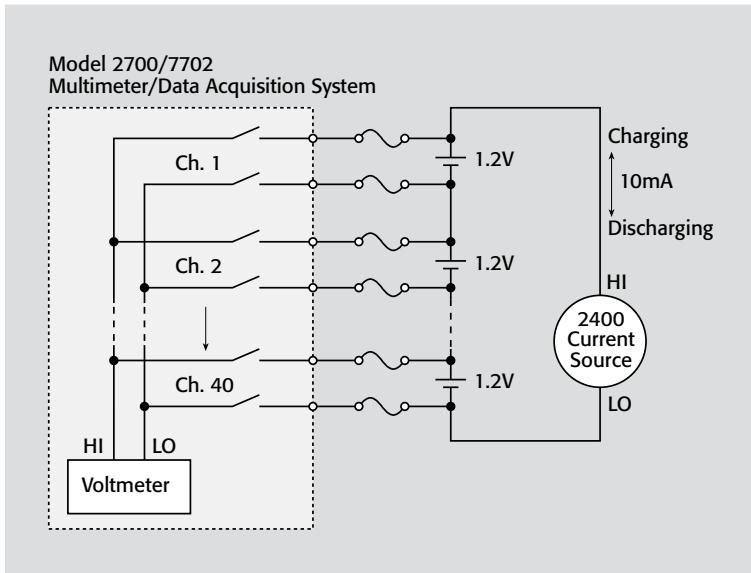
Figure 7-1. Charging/discharging multiple batteries in series

Switching Configurations

Figure 7-1 illustrates the switch configuration for charging/discharging a string of cells connected in series. In this configuration, a series string of 40 cells is connected to a current source (Model 2400 SourceMeter Instrument), which charges/discharges the cells. A separate voltage measurement instrument monitors the individual battery voltages through a switch. (Note: In this application, the Model 2400 cannot be used for both current sourcing and voltage measurement, because it is limited to a 5V difference between the input/output HI and sense HI terminals.)
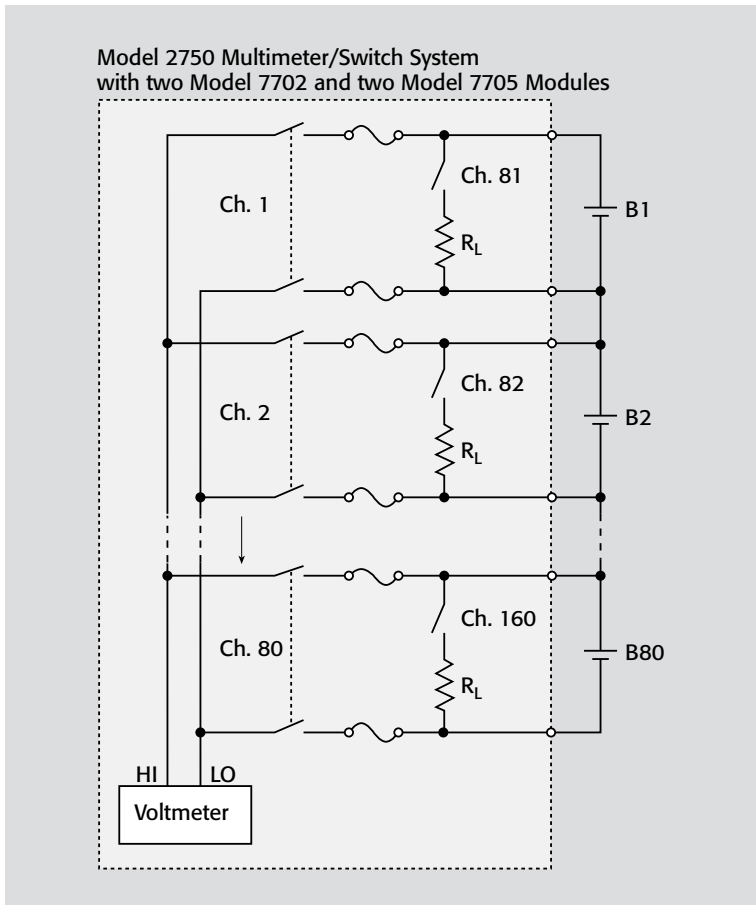
Figure 7-2. Using isolated relays to switch load resistors to batteries

In this particular example, the current source is supplying ±10mA to all 40 cells simultaneously, so all the cells can be either charged or discharged at the same time. The Model 2700 Multimeter/Data Acquisition System, equipped with a Model 7702 40-Channel Differential Multiplexer Module, is used to switch and measure the voltage of each cell. Each cell has a voltage of 1.2V, so the total voltage across the string of cells is 48V. It is important to ensure that the total cell voltage across the string does not exceed the common mode voltage rating and the maximum voltage level of the switch module.

To avoid damage to relays, synchronizing the switch/measure sequence properly is critical. It is particularly important to make certain all other channels are open before closing a particular channel. Inadvertently closing multiple channels will short two or more cells and may damage the relays. Adding a current limiting resistor or fuse in series with each switch will help prevent this type of damage.

To monitor the voltage decay of a series string of cells, load resistors must be switched across individual cells. **Figure 7-2** illustrates a switching system for testing 80 primary cells. In this example, there are two sets of switches: one set of two-pole switches (two Model 7702 modules) is used to connect the cells to the voltmeter, and one set of isolated switches (two Model 7705 40-Channel Control Modules) is used to connect the load resistors (R_L).

If the load resistor was connected directly across the voltmeter input terminals, the current through the relay contacts would cause a voltage drop and the measured cell voltage would be in error. This error is eliminated if isolated relays are used to switch the load resistors to each cell. The Model 7705 module has 40 isolated relays. In addition, these extra isolated relays will allow the load resistors to be connected or disconnected from each cell at any time during the test cycle.

7.2 Capacitor Leakage Measurements

Capacitors are essential components used in practically every type of electronic equipment. Leakage resistance is one of the many electrical characteristics tested on capacitors. The leakage resistance, often referred to as "IR" (insulation resistance), is expressed in megohm-microfarads. In other cases, the leakage may be expressed as a leakage current at a given voltage, usually the operating voltage.

Capacitor leakage is measured by applying a fixed voltage to the capacitor and measuring the resulting current. The leakage current will decay exponentially over time, so it is necessary to apply the voltage for a known period of time (the soak time) before measuring the current.

For statistical purposes, a quantity of capacitors must be tested to produce useful data. An automated switching system is required to make performing these tests practical.

Switching Configuration

Figure 7-3 illustrates a capacitor leakage test system that uses the Model 6517A Electrometer/Source, Model 7158 Low Current Scanner Cards, and Form C Switch Cards, such as the Model 7111-S or 7169A. The cards are installed in a Model 7002 Switch Mainframe.
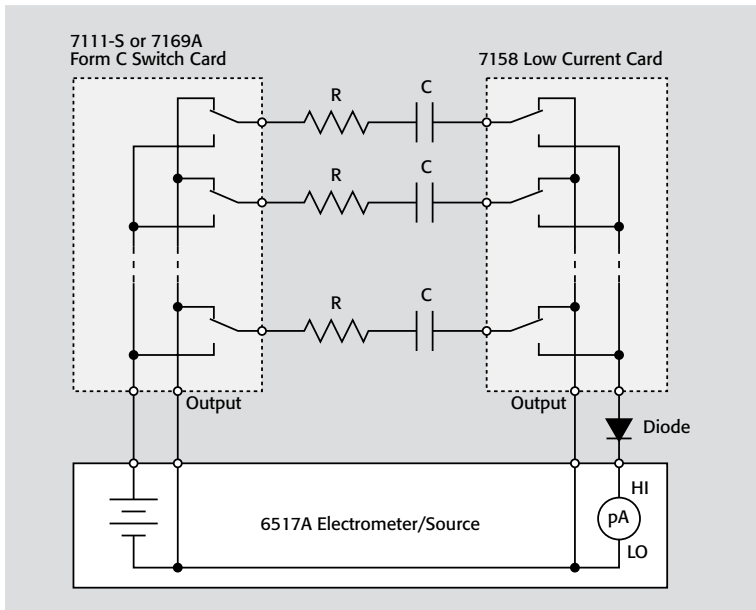
Figure 7-3. Capacitor leakage test system

In this test system, one set of switches (on either the Model 7111-S or 7169A) is used to apply the test voltage to each capacitor. In the normally closed position, one end of the capacitor is connected to circuit LO. When the switch is actuated, the capacitor is connected to the voltage source. Switch actuation is usually staggered (for example, two seconds apart) so that each capacitor may be charged for the same period of time before its leakage is measured. If the maximum test voltage is 110V or less, the Model 7111-S card may be used; otherwise, the Model 7169A card can be used for test voltages up to 500V. If voltages greater than 500V must be applied, use an appropriately rated switch.

A second set of switches (on the Model 7158) connects each capacitor to the picoammeter after a suitable soak period. Note that before the capacitor is switched to the picoammeter, the capacitor is connected to circuit LO. This allows the leakage current to flow continuously while it is being charged up.

For this application, a single instrument provides both the voltage sourcing and the low current measurement functions. The Model 6517A is particularly useful for this application because it can display either resistance or leakage current and will source up to 1000VDC.

After the capacitors have been tested, the voltage source should be set to zero; some time must be allowed for the capacitors to discharge before they are removed from the test fixture. Note that in **Figure 7-3** the capacitors (C) have a discharge path through the normally closed contact of the relays. The test sequence is summarized by:

1. Quiescent state - Model 7169A relays are normally closed and Model 7158 relays are normally closed.

2. Source voltage (soak time) - Model 7169A relays go to normally open and Model 7158 relays remain normally closed.

3. Measure current - Model 7169A relays remain normally open and Model 7158 relays go to normally open.

4. Discharge capacitors - Model 7169A relays go to normally closed and Model 7158 relays go to normally closed.

Since the isolated switches on the Model 7169A Form C Switch Card remain energized during the measurement of current, any offset current from the card is irrelevant to the measurement.

The resistor (R), which is in series with each capacitor, is an important component in this test system. It limits the charging current of each capacitor and also protects the relays in case a capacitor becomes short-circuited. Also, the resistor limits the AC gain of the feedback ammeter. In general, as the source capacitance increases, the noise gain also increases. The resistor limits this gain to a finite value. A reasonable value is one that results in an RC time constant from 0.5 to two seconds. The forward-biased diode in series with the HI electrometer (pA) terminal also serves to limit the AC gain.

A triax-to-BNC adapter (Model 7078-TRX-BNC) is used to connect the Model 6517A to the Model 7158 card. The capacitors are connected to the Model 7158 cards using low noise coax cables. Insulated wires can be used to connect the

Model 7111-S card to the capacitors. The Model 7169A's connections are made through mass terminated connectors.

7.3 Continuity Testing

Continuity checks are typically performed on a variety of devices, including cable assemblies, printed circuit boards, and connectors, to ensure these components have a continuous path where desired. When setting up a continuity test, the engineer must specify the maximum resistance at which the device is considered to be valid. For example, any measured resistance of 1Ω or less would indicate a good device. Continuity checks require measuring low resistance, so a four-wire ohmmeter is normally used to eliminate lead and switch resistance from the measurement.

An isolation resistance or insulation resistance test is often performed in addition to the continuity test. In particular, a multiconductor cable requires each conductor to provide a continuous path from one end to the other; it also requires each conductor to be isolated from all other conductors. Section 7.5 discusses combining continuity and insulation resistance testing.
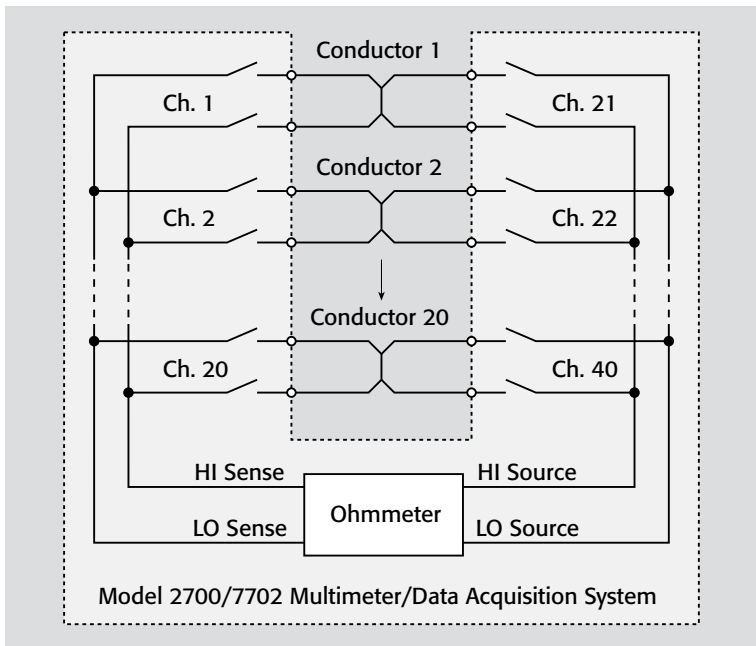
Figure 7-4. Continuity test system

Given that continuity testing often involves multi-conductor devices, a switch system is useful to connect the ohmmeter to each conductor automatically.

Switching Configuration

Figure 7-4 illustrates a typical continuity test circuit. Two banks of two-pole switches are used to make four-wire resistance measurements on 20 conductors. To measure the resistance of Conductor 1 using the Model 2700 Multimeter/Data Acquisition System in the four-wire ohms mode, close Ch. 1. In the four-wire ohms mode, this will automatically close Ch. 21 as well. This is repeated for each conductor.

To measure 20 conductors, a Model 2700 with one Model 7702 40-Channel Differential Multiplexer Module is required. Use a Model 2750 Multimeter/Switch System with multiple Model 7702 modules if more than 40 conductors must be tested at one time.

7.4 Insulation Resistance Testing

The DC insulation resistance (IR) is the ratio of the DC voltage applied between two conductors separated by an insulator to the total current flowing between the two conductors. The test voltage is applied for a specified period of time before the resulting current is measured. The measured current is usually quite small, so a picoammeter or electrometer is often required to make the measurement.

Sometimes the insulation resistance of a sample is measured only to determine that it is greater than a specified minimum value. For example, any resistance value greater than 10MΩ may be considered acceptable. The accuracy of the measurement is not critical; it is only important that the measured resistance be greater than a specified value.

Examples of insulation resistance measurements include measuring the path between traces on a printed circuit board or the resistance between conductors in a multi-conductor cable. IR measurements often involve multiple conductors, so a switching system is often required to switch the picoammeter and the source to all the conductors in the test circuit.

The design and type of switching cards used in an IR test system depend on several factors, including the test voltage, magnitude of resistance, accuracy, common connection, etc. The following section describes two IR test systems.

Switching Configurations

Figure 7-5 illustrates a test system for measuring the IR of any one terminal of a multipin connector to all other terminals using the Model 7111-S 40-Channel Form C Switch Card in a Model 7001 Switch Mainframe. In the de-energized position, the voltage source is connected to all pins under test. When any given channel is selected, the leakage current of that pin to all other pins is measured. The Model 7111-S card has <100pA specified offset current. With a test voltage of 100V, this represents a leakage resistance of 1TΩ. This system in a practical circuit can easily detect leakage resistances of greater than 10GΩ.
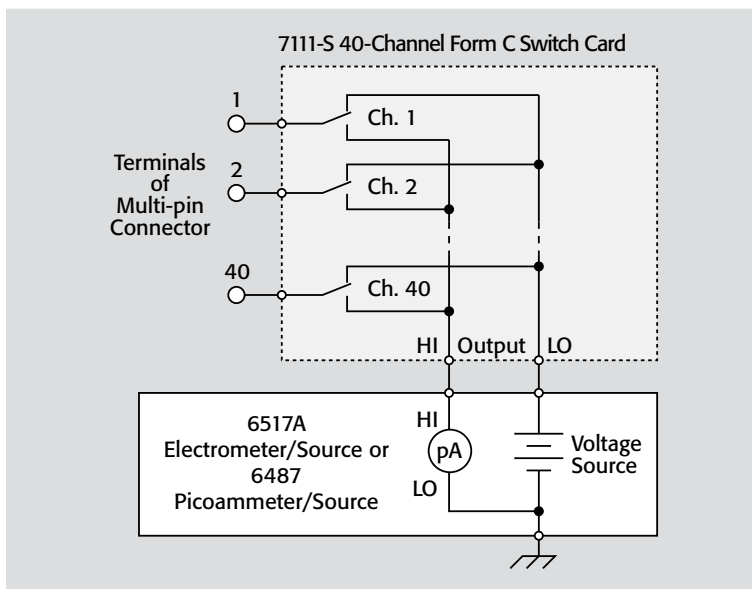
Figure 7-5. Testing IR from any one terminal of a multipin connector to all others

Figure 7-6 shows a system that allows applying the test voltage to one or more terminals while the current is measured from one or more terminals. Note that there are two independent groups of switches connected to each terminal. One group connects the test voltage to the terminals while the other group measures the leakage current. Therefore, the IR can be tested from any terminal to any other or all terminals. Note that all switches will be exposed to the test voltage at some point in the test cycle. Therefore, both groups of switches must be able to withstand the desired test voltage and should have good channel-to-channel isolation to prevent degradation of the measured signal.

In **Figure 7-6**, IR can be measured at relatively high voltage (up to 300V) using Model 3740, a 28-channel isolated Form C switch card. The Model 3740 is used in the Model 3706-S mainframe.

The COM terminal is jumpered on all Form C relays that will be used to change the configuration from switch to multiplex. To measure the insulation resistance between pins 1 and 2, close Channels 1 and 22.
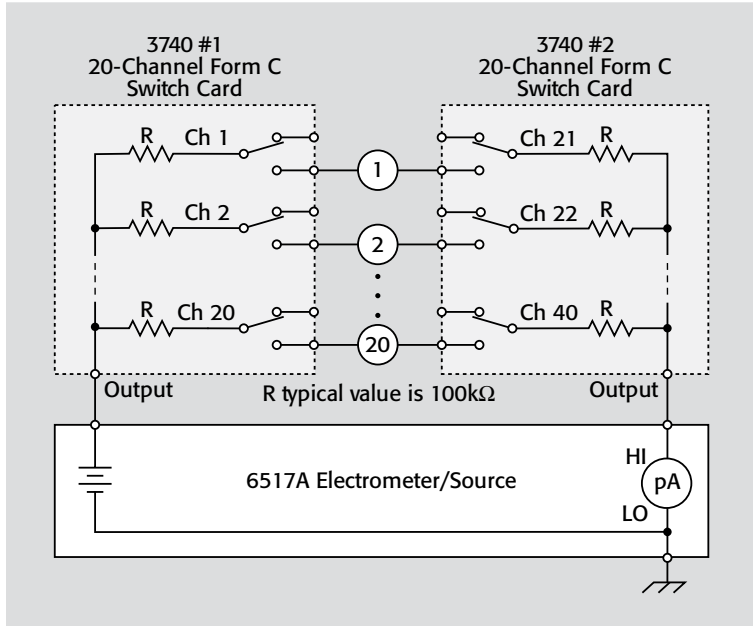
Figure 7-6. Testing IR between any two terminals

The resistors (R) limit the charging current through the relays. These resistors replace factory installed jumpers on the cards to minimize cable capacitance charge and discharge current. A typical R value is 100kΩ.

7.5 Combining Continuity and Insulation Resistance Testing

Some multiple pin devices require measuring the path resistance or continuity through each conductor (a low resistance) and measuring the insulation resistance between the conductors (a very high resistance). This test system requires switching and measuring both low resistance (<1Ω) and very high resistance (>10⁹Ω).

This test system may be used on a variety of devices, such as connectors, switches, multiple conductor cables, and printed circuit boards.

Switching Configurations

Figure 7-7 illustrates a combined continuity and IR system for testing multiple conductors using a four-wire DMM or SourceMeter instrument. The resistances R1 through R20 represent the conductor resistances. To measure conductor resistance R1, close Chs. 1 and 21. The resistances Ra and Rb represent leakage resistance between conductors. The leakage resistance can be measured between any two or more conductors. To measure leakage resistance Ra, close Channels 1 and 22. This is essentially the leakage resistance between conductors 1 and 2, given that Ra is much greater than R1.
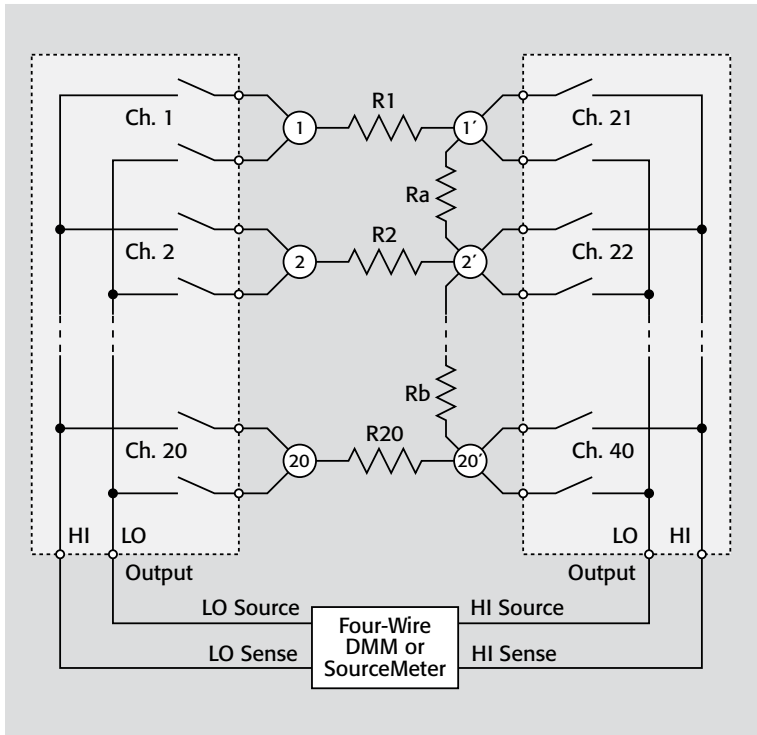
Figure 7-7. Continuity and IR test system

A single Model 2700 Multimeter/Data Acquisition System with a Model 7702 40-Channel Differential Multiplexer can be used to test up to 20 conductors. A

single Model 3706-S with a Model 3722 card can be used to test up to 48 conductors. A fully loaded Model 3706-S with six Model 3722 cards can test up to 288 channels. When measuring the leakage resistance with a DMM, the maximum applied voltage is usually less than 15V. Also, the maximum measured resistance is usually not greater than 100MΩ. To test the IR at a specified test voltage, use a test configuration such as the Model 2400 SourceMeter instrument with Model 7011 Quad 1×10 Multiplexer Cards in a Model 7001 or 7002 Switch Mainframe.

If a higher test voltage is required or if a higher leakage resistance must be measured, the circuit in **Figure 7-8** may be used. In this diagram, two Model
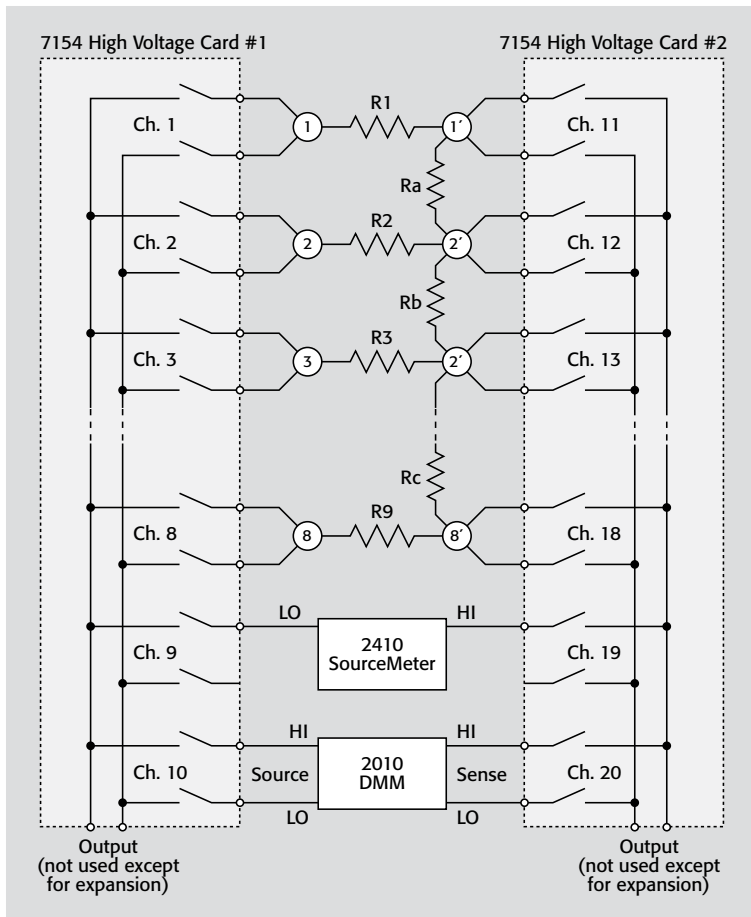
Figure 7-8. Expanded range continuity/IR system

7154 High Voltage Scanner Cards are used to switch a Model 2410 SourceMeter instrument and Model 2010 Digital Multimeter to eight conductors. This system can measure conductor resistances as low as 0.1mΩ and leakage resistances as high as 300GΩ with a test voltage as high as 1000V. Note that the Model 2410 and Model 2010 are not connected to the card outputs, but are connected to specific channels of the scanner cards. The outputs of the cards are only used to expand the system to measure a larger number of conductors. To measure the resistance of R1, close Chs. 1, 10, 11, and 20. This will connect the Model 2010 across R1. To measure Ra, the leakage resistance between R1 and R2, close Chs. 1, 9, 12, and 19. This will connect the Model 2410 across the leakage resistance (Ra).

7.6 Insulation Resistance Testing of Printed Circuit Boards

Printed circuit boards (PCBs) are used in most electronic products. If a PCB has low insulation resistance (IR), it can degrade the performance of the circuits on the board considerably. Factors that affect the surface resistance of the board include the board material, the presence of coatings such as solder masking or conformal coatings, and board cleanliness. Temperature and relative humidity can also affect the surface resistance.

To test the insulation resistance, special test patterns called coupons are created on printed circuit boards. The resistance typically ranges from $10^7Ω$ to $10^{16}Ω$ and is measured with a picoammeter and voltage source. The test coupons usually have several terminals, so test systems include scanners to switch the picoammeter and the voltage source to the terminals.

Switching Configurations

Figure 7-9 outlines a system to test a single five-terminal ("W") test pattern. In this circuit, the Model 7011 Quad 1×10 Multiplexer Card is used to connect the voltage source to terminals 1 and 5 together or to terminal 3. The Model 7158 Low Current Switch Card is used to connect the electrometer to terminal 2 or 4.

At the start of the measurement, close Ch. 1. After a specified "soak" time, energize Ch. 41 and measure the current. The ratio of the applied voltage to the measured current is the resistance between terminals 1 and 2. Next, de-energize Ch. 41 and energize Ch. 42 to measure the insulation resistance between terminals 5 and 4. Note that the path from 5 to 4 already has been biased. No additional soak time is needed, so it can be measured immediately. De-energize Ch. 42, then open Ch. 1 and close Ch. 2 to apply the test voltage to terminal 3. The 1MΩ resistor located at Ch. 1 will discharge the voltage at terminals 1 and 5, so it will not interfere with subsequent measurements. After the specified soak time, energize Ch. 41
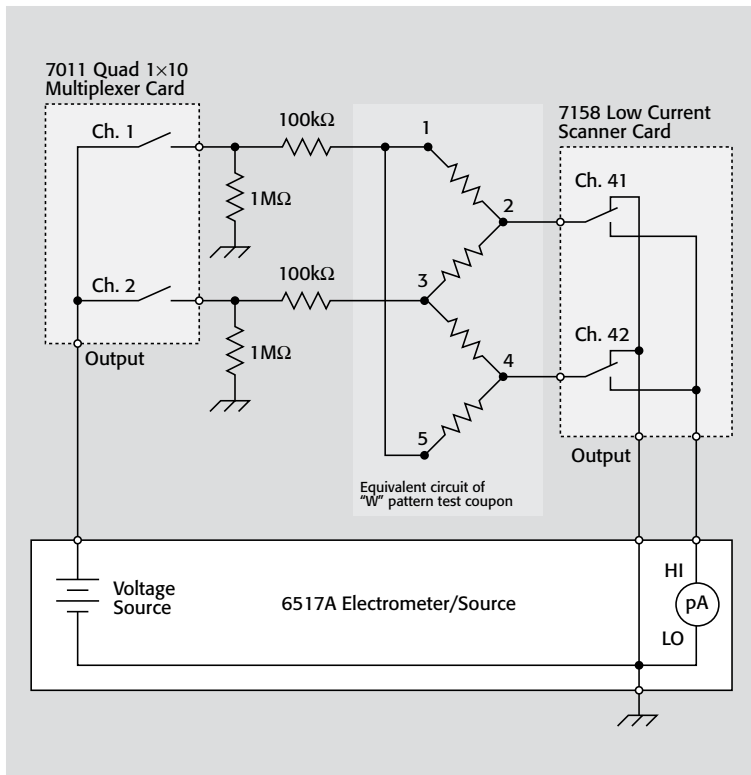
**Figure 7-9. System to test the insulation resistance of one test coupon**

again to measure the resistance between terminals 3 and 2. De-energize Ch. 41 and energize Ch. 42 to measure the resistance between terminals 3 and 4, which already has been biased.

Note that when none of the channels on the Model 7158 card are energized, terminals 2 and 4 are connected to the LO of the picoammeter (pA), which electrically is the guard terminal. This guard connection will prevent leakage current from de-energized channels from interfering with the measurement.

Five "W" patterns can be tested as described using one Model 7011 card and one Model 7158 card. Model 7111 Form C Switch Cards can be used in place of the Model 7011 card. If this card is used, de-energizing a channel will connect the terminal to circuit LO rather than the voltage source. This will eliminate the need for the 1MΩ resistors. When using either the Model 7011 or 7111 Cards, the test voltage cannot exceed 110V.

The 100kΩ resistors are used to limit the available current in the event of a short-circuited test coupon. Choose current limiting resistors that are no more than 10% of the lowest measured resistance.

Figure 7-10 shows a circuit to test a coupon with ten two-terminal leakage paths. Each coupon can be thought of as a bank of isolated resistors (R1, R2, R3, R4, etc.). Each resistor requires one voltage channel and one current channel. The Model 7158 card connects the electrometer or picoammeter to one end of each resistor, while the Model 7111-S 40-Channel Form C Switch Card connects the voltage source to the other end of each resistor.
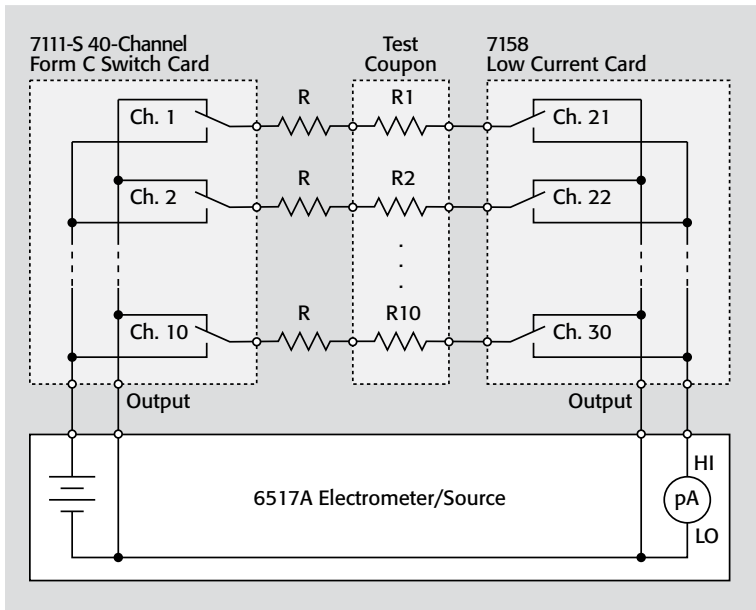
Figure 7-10. Circuit to test a single ten-resistor coupon

To test resistor R1, first energize Ch. 1 to bias the test coupon. After a specified "soak" period, energize Ch. 21 to measure the resulting current. Continue this process for all of the remaining resistances.

Note that when the channels are de-energized, the corresponding resistor terminals are connected to circuit LO, allowing any charge across the resistances to be dissipated when the resistance is not being measured.

The current limiting resistors (R) protect the scanner cards from damage if the test coupon develops a short circuit.

Low noise coax cables should be used between the test coupons and the Model 7158 cards to avoid noise currents.

7.7 Contact Resistance

Contact resistance is the resistance to current flow through a closed pair of contacts. These types of measurements are made on components such as connectors, relays, and switches. This resistance is normally very small, ranging from micro-ohms to a few milliohms, so a four-wire measurement method is used. Programmable scanners greatly reduce measurement time by switching one set of test instruments to multiple contacts, such as when testing multi-terminal connectors or when testing many contacts automatically in an environmental chamber.
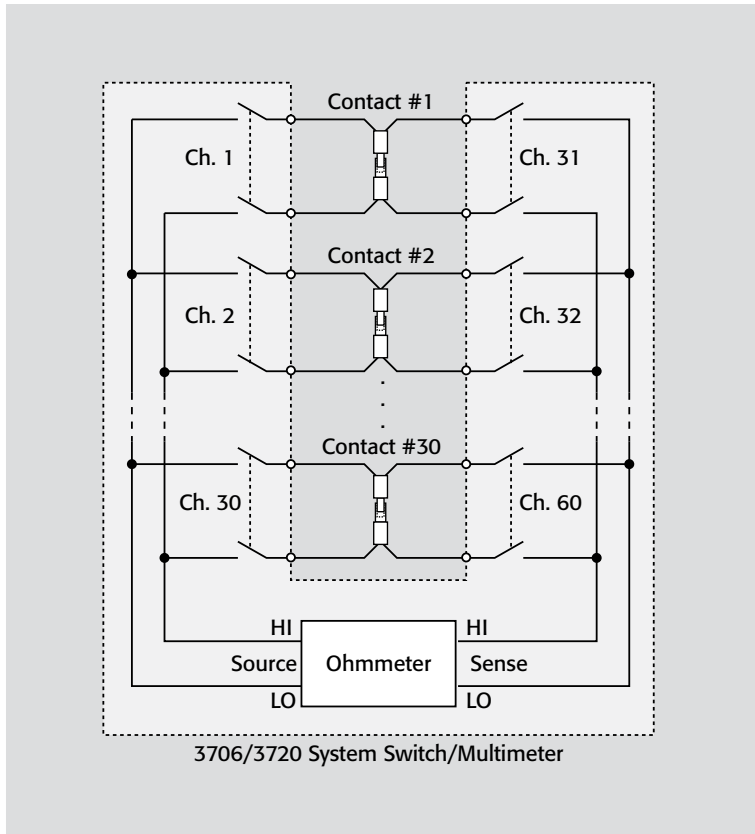
Figure 7-11. Measuring resistance of 30 contacts

Switching Configurations

As **Figure 7-11** shows, all four terminals of the ohmmeter are switched in order to prevent the test lead, path, and switch contact resistances from being added into the measurement. Note the HI and LO Source terminals are connected to one set of two-pole switches, while the HI and LO Sense terminals are connected to another set of two-pole switches. To measure the resistance of Contact 1, close both Chs. 1 and 21, then measure the resistance with the ohmmeter. To measure Contact 2, open Chs. 1 and 21, close Chs. 2 and 22, then measure the resistance again.

A Model 3706 System Switch/Multimeter can be used to measure the contact resistance because it can measure resistances less than 1mΩ and offers offset compensation and dry circuit testing capabilities.

Contacts used in low level applications are often tested under dry circuit conditions, in which current and voltages are limited to levels that cannot cause changes in the physical and electrical condition of the contact junction. In general, a dry circuit is one in which the open circuit voltage is low, usually 20mV or less, and the short circuit current is limited to 100mA or less.
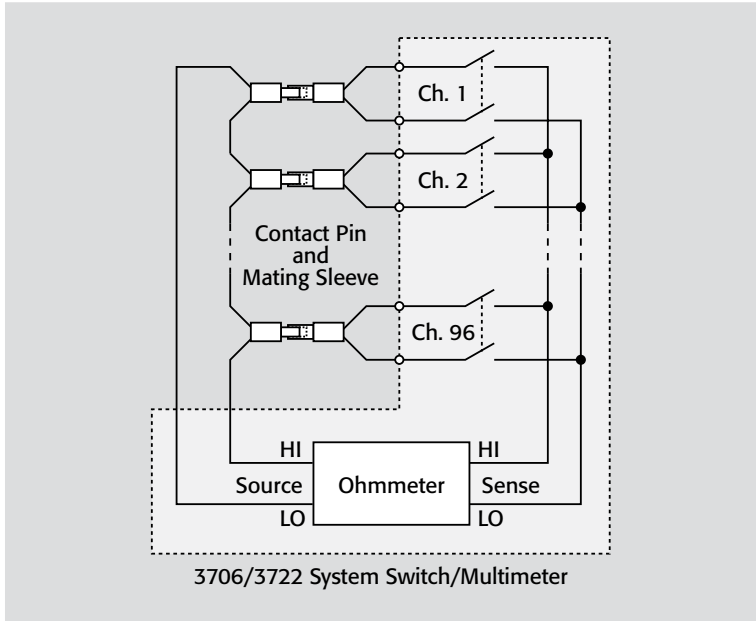
Figure 7-12. Measuring 96 contacts with a common terminal

In some cases, the number of switches required may be reduced by half by connecting the samples in a unique series manner, as shown in **Figure 7-12**. In this example, all the contact pins are connected in series and each of the mating sleeves is connected to a two-pole switch. In this case, a Model 3706 System Switch/Multimeter is configured with a Model 3721 Dual 1×20 Multiplexer Card and can test up to 40 contacts. Up to 240 contacts can be tested using six Model 3721 modules in one Model 3706 mainframe.

Figure 7-13 illustrates a high-performance contact resistance system for measuring very low resistances ($\mu\Omega$) at relatively low currents (<100μA). In this system, a Model 6220 or 6221 Current Source outputs the test current and a Model 2182A Nanovoltmeter measures the voltage drop across each contact. Both the Model 2182A and the Model 622x are switched to each contact using a Model 7011 40-Channel Multiplexer Card. The Model 622x has a programmable voltage compliance limit, so this system can ensure dry circuit testing conditions.
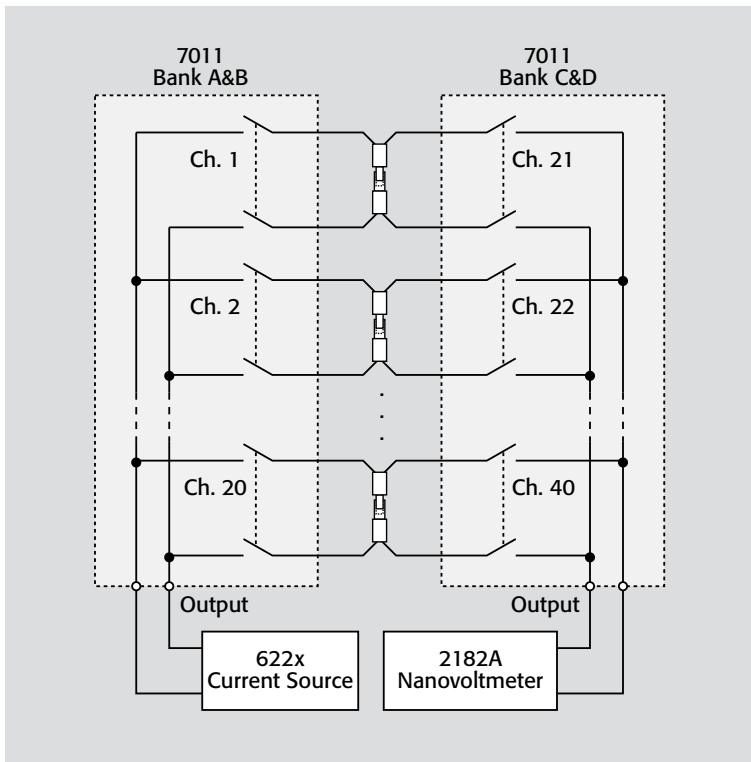
Figure 7-13. High performance contact resistance system

Twenty contacts can be switched using one Model 7011 card and one Model 7001 Switch Mainframe. The Model 7011 card is configured into two 20-channel banks. Two relays can be simultaneously opened or closed automatically by using the mainframe's four-pole switch mode.

7.8 Temperature Scanning

Temperature is one of the most commonly measured physical parameters. Temperature is often monitored at several locations, so a scanner is required to switch the measuring instrument to multiple sensors. The type of measuring instrument and scanner card used depends on the type of temperature sensor employed. Three common sensor types are thermocouples, platinum RTDs, and thermistors. When deciding which temperature sensor to use, keep in mind that the thermocouple is the most versatile, the four-wire RTD is the most accurate, and the thermistor is the most sensitive. The use of these sensors is discussed in the following switching configurations.

Switching Configurations

Thermocouples

Thermocouples are the most widely used temperature sensors. They can cover a wide temperature range and provide a robust, reliable sensor. The measured thermocouple voltage is related to the difference between the unknown temperature and a reference temperature. This reference temperature is determined from the cold junction reference (CJR). When thermocouples are to be switched, the reference temperature may be obtained from an internal reference junction located on the switch card, a simulated reference temperature, or an external reference junction. The choice of reference junction is limited by the choice of switch card and by the method of cold junction compensation implemented by the measuring instrument.

Built-In (Internal) Reference Junction. This is the most convenient method to use if the switch card includes the temperature reference. This reference junction is built into the switch module and uses a thermistor, a solid-state sensor, or other type of temperature sensor. Switch modules with built-in CJRs include the Models 7700, 7706, and 7708 modules for the Model 2700/2701/2750 Multimeter/Data Acquisition/Switch Systems. Switch modules with built-in CJCs include Models 3720 and 3721 for the Model 3706-S mainframe. The Model 2001-TCSCAN 9-Channel Thermocouple Scanner Card for the Models 2000, 2001, 2002, and 2010 DMMs also has a built-in CJR.

Figure 7-14 shows multiple thermocouples connected to the Model 3706 with a Model 3720 Dual 1×20 Multiplexer Card installed. The Model 3720 has several

strategically placed cold junction references to monitor the junction temperatures on the screw terminal card. When the temperature of thermocouple T1 is to be measured, the meter first measures the nearby CJR. When Ch. 1 is closed, the voltage of thermocouple T1 is measured and the temperature reading at the thermocouple is calculated. The Model 2700 with a Model 7700 card can also be used for this application.
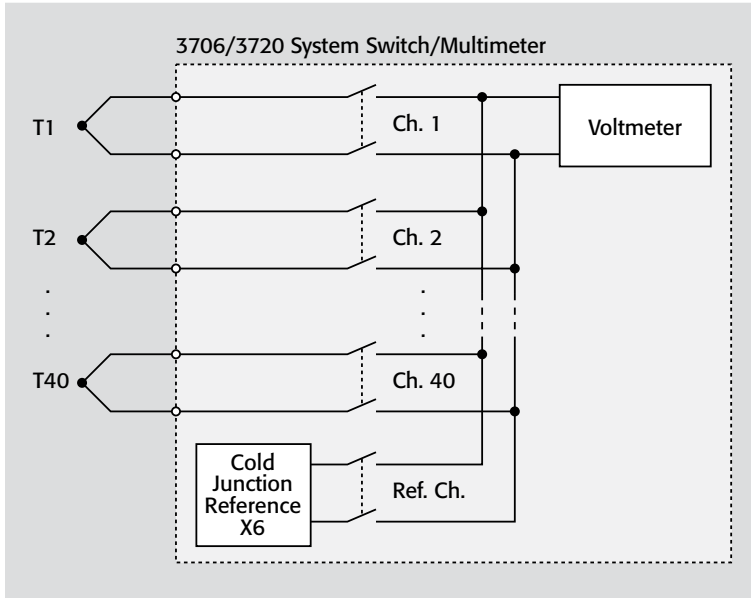

Figure 7-14. Using the internal reference junction of the Model 3706/3720

As an alternative to using multiple CJRs, some switch cards employ an on-board isothermal block to keep all the connection terminals at the same temperature. The Model 7014 Thermocouple Card and Model 2001-TCSCAN Thermocouple Scanner Card have isothermal blocks.

Simulated Reference Temperature. In this case, the user inputs a temperature value that approximates the temperature at the input terminals of the DMM. The DMM uses this simulated reference temperature in calculating the temperature at the thermocouple. The simulated reference temperature technique can be used with the Models 2000, 2001, 2002, 2010, 2700, 2701, 2750, and 3706-S. The accuracy of the measurements will depend on the accuracy of the simulated

temperature. If the ambient temperature changes, then the accuracy of the thermocouple measurements will be degraded.

One method of using a simulated reference temperature is to input the approximate temperature at the location where the thermocouples are connected to the switch card. The reference temperature used should reflect the effects of instrument self-heating, not simply the room's ambient temperature. **Figure 7-15** illustrates the use of this method. In this case, the temperature reference is at the Model 7702 40-Channel Differential Multiplexer Module's input terminals; therefore, the user must input a best guess of the temperature at these input terminals of the switch module. This is the least accurate way to make temperature measurements, because it requires the user to approximate the reference temperature and does not account for changes in the ambient temperature or thermal gradients across the card. However, this method is the least expensive because a general-purpose switch card or module can be used.
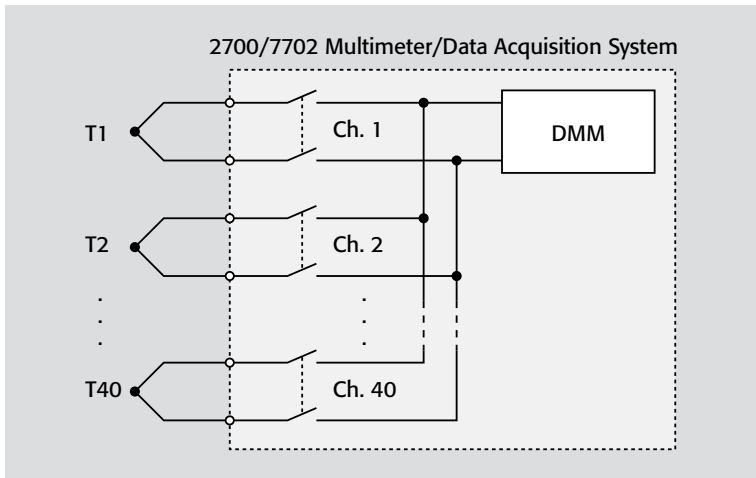
Figure 7-15. Using simulated reference temperature with the Model 2700/7702

Figure 7-16 illustrates the use of an ice point as the reference temperature. In this example, a second thermocouple in an ice bath is connected in series back-to-back with each measurement thermocouple. Using this ice point reference is usually the most accurate way to make temperature measurements. To measure the voltage of thermocouple T1, close Ch. 1. The measured voltage is proportional to the temperature T1 with a reference of 0°C. If a meter such as the Model 2700/7702 is being used, simply enter this 0°C reference in the meter

as the simulated reference temperature. The Model 2700 will then automatically calculate the temperature T1 based on the measured voltage.
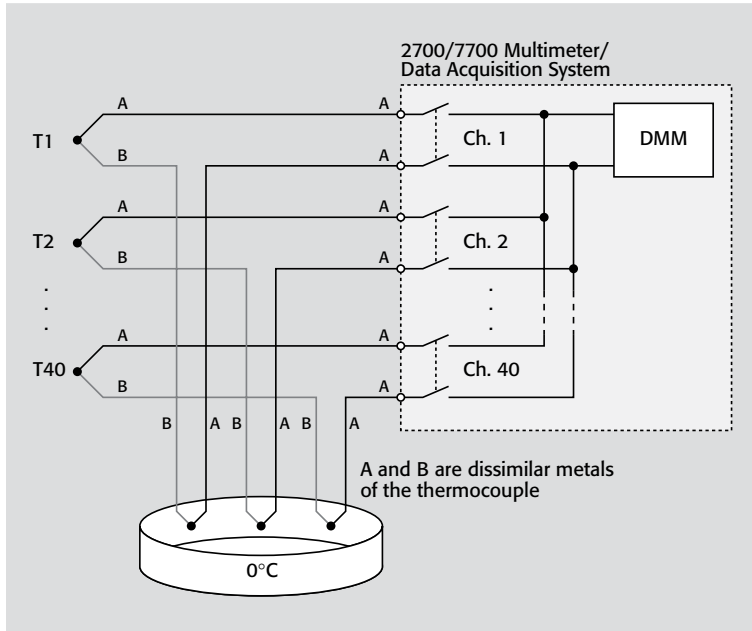
Figure 7-16. Using "back-to-back" thermocouples and a 0°C reference temperature

External Reference Junction. For switching modules that do not have built-in reference junctions, a thermistor or four-wire RTD can be used to acquire the reference temperature, such as with the Model 2700, 2701, 2750, or 3706-S. In this case, a thermistor is connected to Ch. 1 or a four-wire RTD is connected to Ch. 1 and its paired channel. **Figure 7-17** shows an example of a thermistor used as the external temperature sensor. To measure the cold junction temperature, close Ch. 1. The Model 2700, 2701, 2750, or 3706-S automatically measures the thermistor resistance and calculates the temperature at the sensor. This temperature reading is used by the instrument as the reference temperature for subsequent thermocouple measurements.

The thermistor or RTD should be positioned near the terminals of the channels being used for thermocouple temperature measurements. The leads of this temperature sensor should be insulated to prevent contact with other conductors on the module.
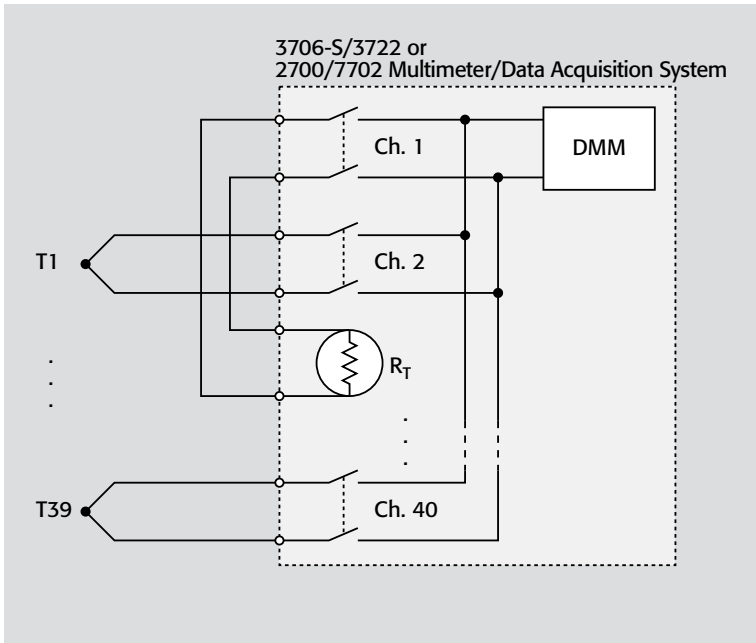
Figure 7-17. Using a thermistor as an external reference junction

The accuracy of this method depends on how closely coupled the temperature sensor is to the thermocouple terminals.

Platinum RTDs

Platinum RTDs may be either wire-wound resistors or thin-film resistors that exhibit a positive temperature coefficient of about 0.4%/°C.

Platinum RTDs offer excellent long-term stability, high accuracy, and good repeatability. Unlike thermocouples, RTDs do not require cold junction compensation. However, RTDs operate over a narrower temperature span, respond more slowly, and are generally more expensive and more fragile than thermocouples.

Figure 7-18 illustrates a system to measure temperature using RTDs. Twenty RTDs are connected through four-pole switches to a Model 2700 configured as a four-wire ohmmeter. With the Model 2700 and a Model 7702 module, 20 RTDs can be connected and the meter will convert the resistance measurements to temperature automatically. With the Model 3706-S and a Model 3722 card, 48 RTDs can be connected and measured.
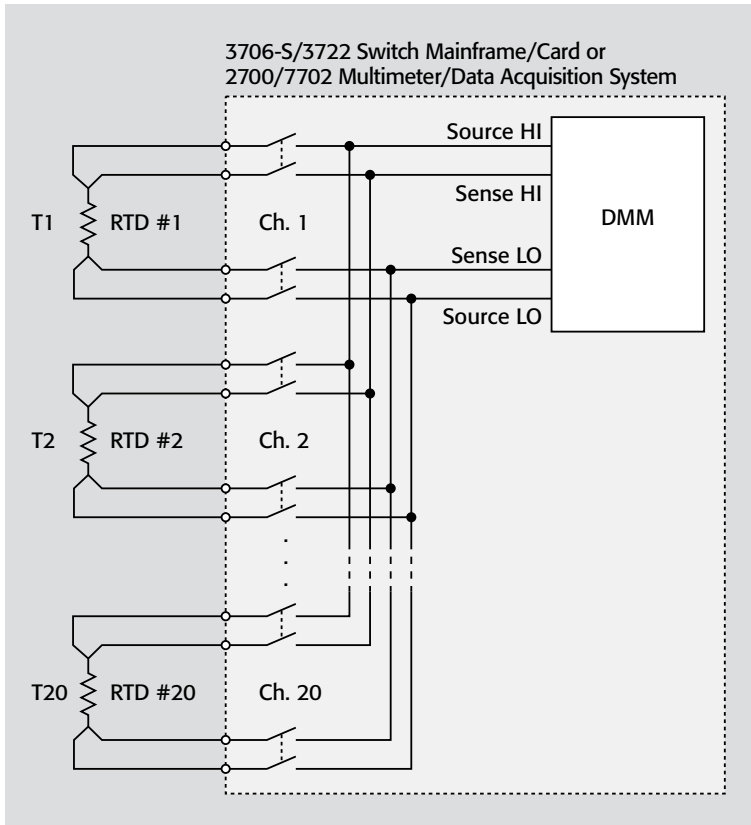
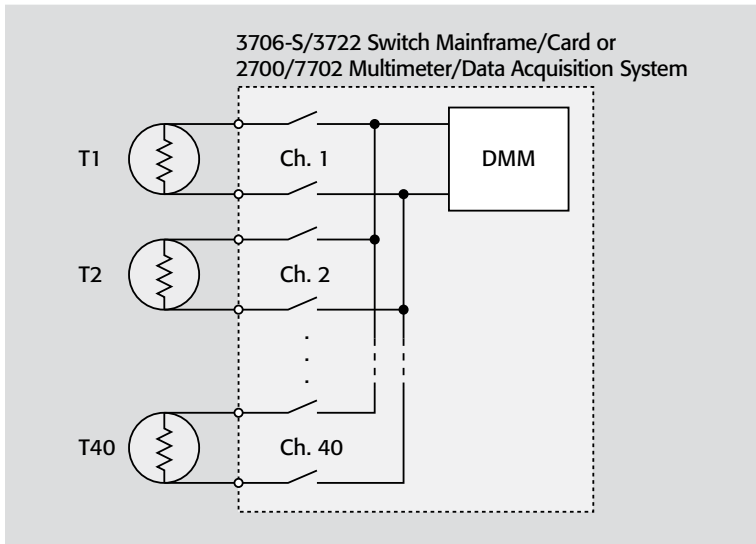**Figure 7-18. Measuring temperature using RTDs**

Thermistors

Thermistors are devices that exhibit a non-linear change in resistance with a change in temperature. Most thermistors have a negative temperature coefficient—in other words, as the temperature increases, the resistance decreases.

Thermistors are the most sensitive of all the temperature sensors and can detect very small changes in temperature quickly. They are a good choice when measuring very small changes in temperature. The downside of this increased sensitivity is a loss of linearity. They are especially non-linear at high temperatures, so it is best to use them for measurements of less than 100°C.

Figure 7-19 outlines a system for measuring temperature using thermistors. Note that a two-wire resistance measurement is adequate, given that thermistors

are usually in the kilo-ohm ranges; therefore, switch and lead resistances have little effect on the overall measurement. To convert the resistance measurement to temperature, it is best to use an instrument that can correct for a thermistor's non-linearity automatically, such as the Model 2700, 2701, 2750, or 3706-S. One Model 7702 module installed in a Model 2700 can accommodate up to 40 thermistors. One Model 3722 card installed in a Model 3706-S mainframe can accommodate up to 96 thermistors.


Figure 7-19. Measuring temperature using thermistors

7.9 Diode Testing

Diodes are widely used non-linear components. When testing diodes, the electrical parameters measured include the forward voltage, the reverse breakdown voltage, and the leakage current. These specific tests can be measured with a single source-measure instrument. When testing multi-diode devices, such as pin grid arrays or DIP packages, switching is required to connect a single source-measure instrument to each individual diode.

Switching Configurations

Figure 7-20 shows an example of testing multiple diodes in a switching system. This configuration can be used for measuring the forward voltage, the reverse breakdown voltage, and the leakage current. This type of system is often used for
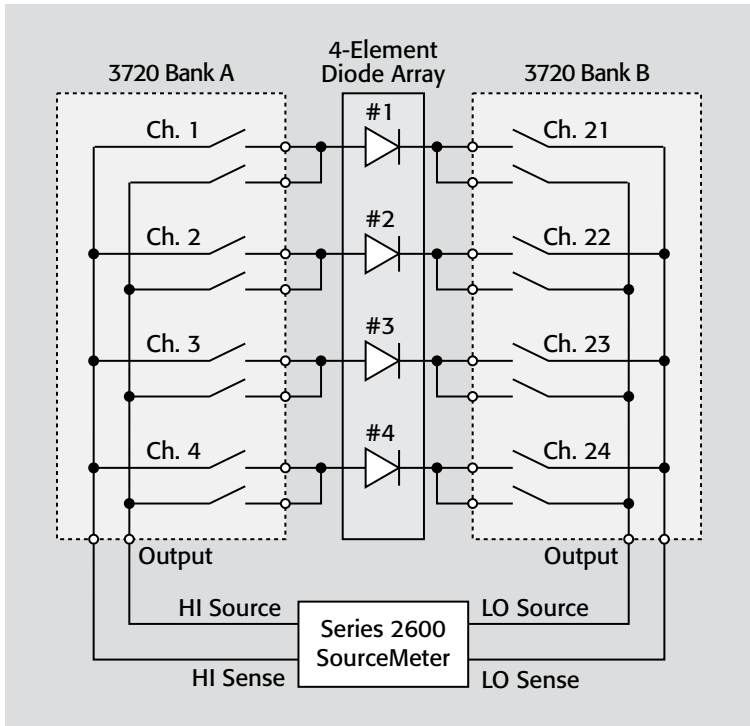
Figure 7-20. Switching multiple diodes to a Series 2600 System SourceMeter instrument

production tests in which performing single point pass/fail DC tests on packaged diodes ensures compliance with specifications and sorts out defective parts.

In this system, each diode is switched to the Series 2600 System SourceMeter instrument through two two-pole switches. The Series 2600 instrument can source and measure both current and voltage.

To connect the System SourceMeter instrument to diode 1, close Chs. 1 and 21. To measure the forward voltage, apply the specified current, then measure the resulting voltage drop. Measure the reverse breakdown voltage by sourcing a specified reverse current bias, then measuring the voltage drop across the diode. To perform the leakage current test, source a specified reverse voltage, then measure the resulting leakage current. Repeat this procedure for all the diodes.

Note that two two-pole relays are used to connect each diode to the Series 2600. This is done to eliminate error from the voltage drop in the lead resistance.

(Offset voltages of the Model 3720 switches can be addressed with the offset-compensated ohms feature of the Series 2600 instrument.) This is particularly important when measuring the forward voltage, because the measured voltages are relatively small (hundreds of millivolts) and the source current may be relatively high (100mA).

For the example in **Figure 7-20**, two-pole general-purpose cards, such as the Model 3720 Dual 1×30 Multiplexer Card, can be used. One Model 3720 card will support testing up to 30 diodes.

For measuring smaller leakage currents (<10nA), use the configuration shown in **Figure 7-21**. In this example, the Model 7158 Low Current Scanner Card is used to switch ten diodes with a common cathode to the Model 6517A Electrometer/Source.
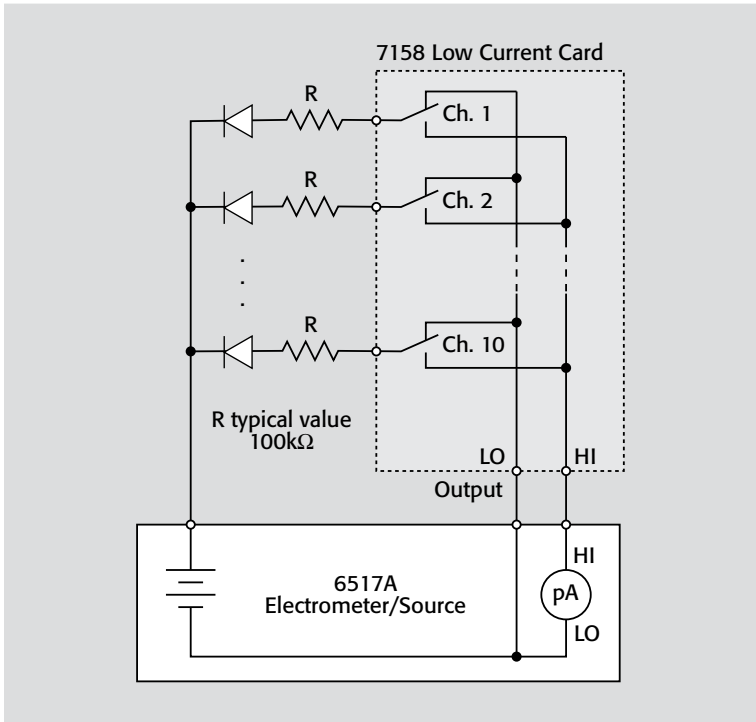
Figure 7-21. Measuring the leakage current of ten diodes

When measuring the leakage current with this setup, the voltage bias is applied to all the diodes simultaneously through the normally closed contact of each

relay. When a particular channel is energized, the leakage current for that diode will be measured. The current limiting resistor (R) is included to prevent test failure in the event a diode is short-circuited.

Figure 7-22 shows a configuration for testing leakage current of diodes using a Source-Measure Unit (SMU) or a SourceMeter Instrument. In this example, the Output HI terminal of the SMU is connected to the normally open output terminal of the Model 7111-S 40 Channel Form C Switch Card. The Guard terminal of the SMU is connected to the normally closed output terminal of the switch card. The guard voltage is at the same potential as the Output HI terminal, so the test voltage is applied to all diodes at all times through the guard connection. If the SMU is set for a positive output voltage, the diodes will be reverse biased. The Output LO terminal of the SMU is connected to the common anode terminal of the diodes.
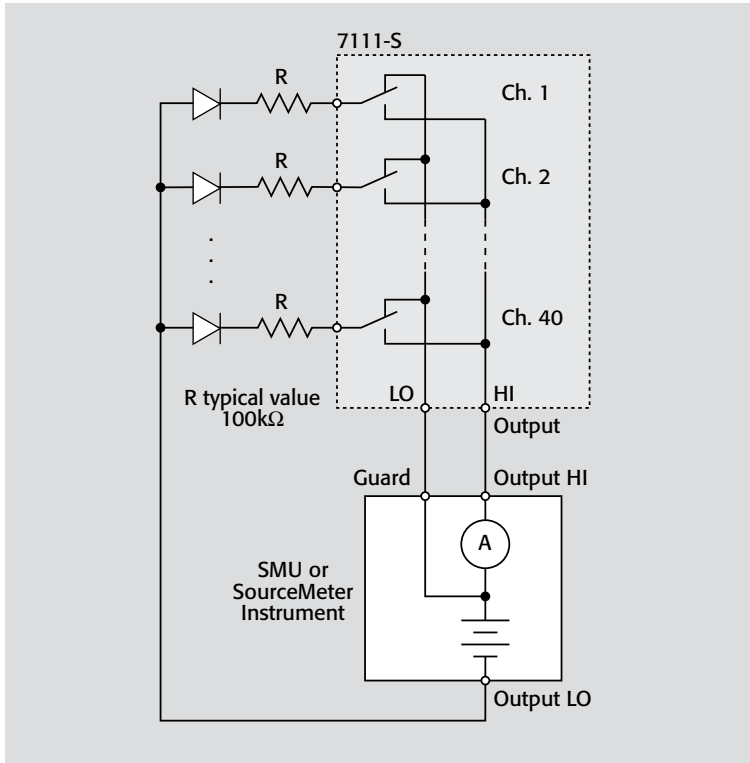
Figure 7-22. Using an SMU or SourceMeter Instrument to test the leakage current of diodes

7.10 **Capacitance Measurements**

Capacitance measurements are made to verify that capacitors meet their manufacturer's specifications. For quality control purposes, a group of capacitors may be placed in an environmental chamber and the capacitance of each capacitor tested. Multiple switches connect the capacitors to the capacitance meter.

Test frequency and stray capacitance may impose limitations when switching capacitance. Capacitance measurements are often made at a high frequency (kHz –MHz ranges), so it's important to choose switches carefully to avoid errors due to bandwidth limitations. The capacitance introduced to the system by both the switches and the cable must be corrected for by the LCR meter by using open and short circuit calibration; therefore, it is important to determine if a particular LCR meter is capable of performing the necessary corrections.

### **Switching Configurations**

In **Figure 7-23**, the Model 7011-S Quad 1×10 Multiplexer Card connects an LCR meter to a number of unknown capacitors (C1 through C8). For any given capacitor measurement, four relays, one in each bank, must be closed. The outputs of the four banks are connected to the LCR meter's four input terminals.

The Model 7011-S card allows making four-wire connections to as many as ten capacitors. However, two sets of channels should be used to perform open and short calibration, so the system can only test up to eight capacitors. When performing the open calibration, the HI CURR and HI POT leads must be connected together using Ch. 9 of each bank; the LO CURR and LO POT leads must also be connected together. When performing the short calibration, all four leads are connected together using Ch. 10 of each bank.

The shields of the four coaxial cables connected to the unknown capacitors are connected to each other. This connection should be made near the capacitor for best accuracy. For simplicity, the shields are not shown in **Figure 7-23**. Space limitations on the Model 7011-S card make it necessary to use sub-miniature coax cables. The length of the coaxial cables for all channels should be approximately the same.

With the Model 7011-S card, the test frequency may be as high as 100kHz. The minimum unknown capacitance that can be switched with this card is on the order of 10pF. There is no maximum capacitance other than determined by the card's maximum current rating.

The system shown can be expanded easily by adding more Model 7011-S cards. The backplane of the scanner mainframe will connect the appropriate banks
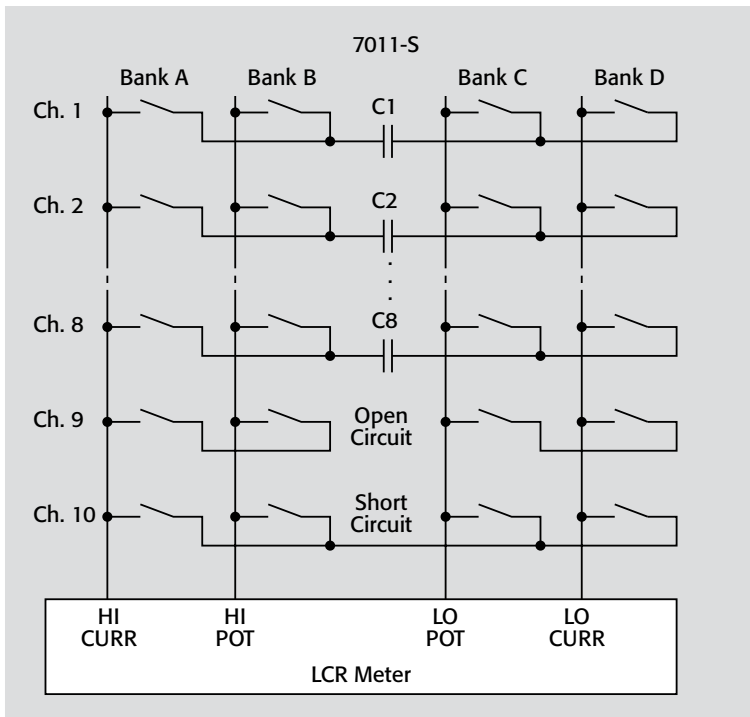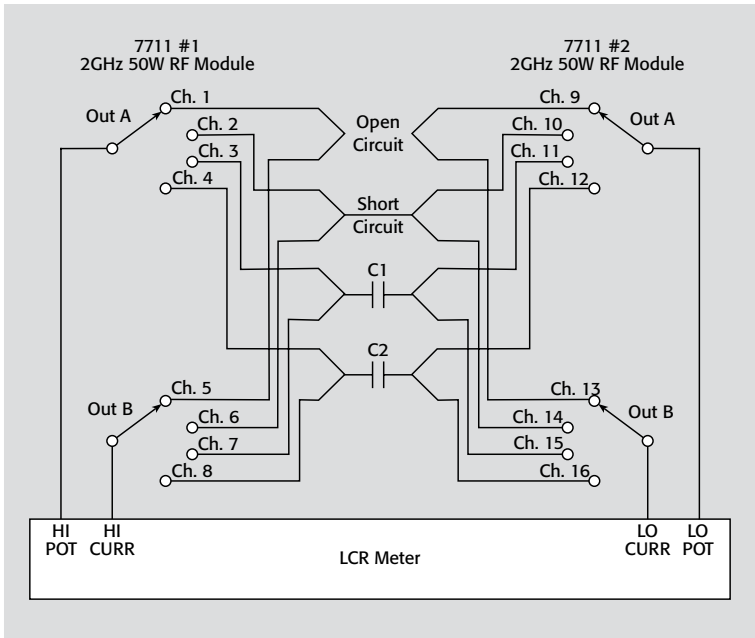
Figure 7-23. Capacitance measurement using a Model 7011-S card

of each card. Remove any bank-to-bank jumpers from all cards. As more switch cards are added to expand the system, the maximum allowable test frequency may decrease.

The Model 7011-C version is not recommended for this application because the added coupling due to this card's mass-terminated connectors may cause an unacceptable amount of error.

To measure capacitors at 1MHz or higher, an RF switch card, such as the Model 7711 2GHz 50Ω RF Module, is essential. The Model 7711 consists of two banks of 1×4 multiplexers. As shown in **Figure 7-24**, two Model 7711 modules provide four-terminal connections from a four-terminal capacitance bridge to test up to two capacitors. One module switches the HI terminals of the bridge, while the second module switches the LO terminals.

The second channel of each bank is connected to a jumper to allow short-circuit calibration. When no channels are selected, the first channel of each bank, which

Figure 7-24. High frequency capacitance measurements with two Model 7711 modules

is normally-closed, is connected to an output port. By connecting coax cables to all four output ports as shown, an open-circuit calibration can be performed. Again, note that these cables should be the same length as those for the other channels.

To expand the system and allow testing more capacitors, additional switching modules are needed. With two inputs of one bank connected to the outputs of another module, 1×8 multiplexers are possible instead of 1×4 multiplexers. This system, with a total of six Model 7711 modules, will test up to six capacitors. Similarly, by connecting two modules to yield 1×12 multiplexers, a total of eight modules will test up to ten capacitors.

Figure 7-25 illustrates a system that measures both the capacitance and leakage current of capacitors. In this diagram, note the picoammeter (pA) and LCR meter are connected to the capacitors under test via Chs. 9 and 10, respectively. The output ports on the Model 7011-S card have no connections. However, the output ports would be used to increase the total number of capacitors being tested by adding more cards.
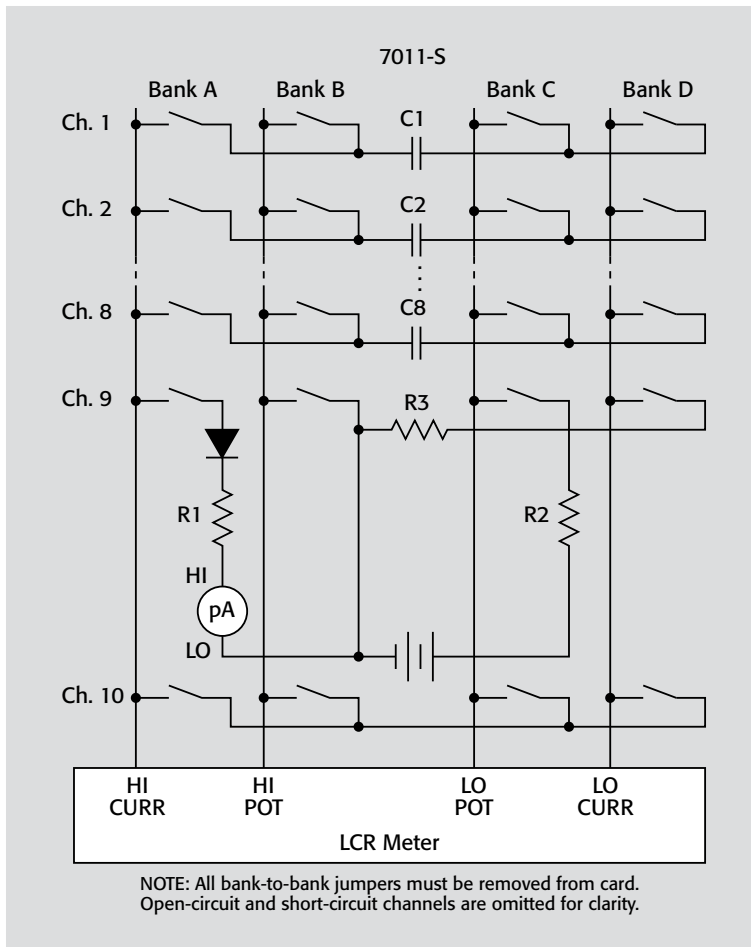
Figure 7-25. Measuring capacitance and leakage current with a Model 7011-S card

To measure the leakage current of C1, the capacitor must first be polarized by closing Chs. 1 and 9 of both Banks B and C. This connects the voltage source across to the capacitor through the current limiting resistor, R2. After an appropriate "soak" time, close both Ch. 1/Bank A and Ch. 9/Bank A to connect the picoammeter to the capacitor, then open Ch. 9/Bank B to avoid short-circuiting the picoammeter. Once the leakage has been measured, the capacitor should be discharged by first opening Ch. 9/Bank A and Ch. 9/Bank C. Then close Ch. 9 on Bank B and Bank D, which will place resistor R3 across capacitor C1.

The diode and resistor R1, in series with the picoammeter input, serve two functions. First, the resistor will limit the current in case a capacitor becomes shorted. Second, the diode minimizes the picoammeter noise introduced when measuring capacitors of 1nF or greater. The diode is photosensitive, so it should be enclosed with R1 in a light-tight electrostatic shield.

The capacitance of C1 can now be measured by first opening Ch. 9, Banks B and D, then closing Ch. 10, Banks A through D. This will connect the LCR bridge to capacitor C1. Ensure that all capacitors are discharged before connecting the LCR bridge.

This system is relatively low in cost; however, it has several performance limitations:

• The maximum test voltage is 110VDC. It is capable of measuring a leakage current of 1nA with fair accuracy, so it can verify capacitor leakage resistance of 100V/1nA or 100GΩ.

• The LCR bridge test frequency should be no more than 100kHz.

• The minimum capacitance that can be measured is on the order of 10pF.

7.11 Accelerated Lifetime Testing of Cellular Phone Handsets

Lifetime testing is one of the most common types of production tests that cell phone handsets undergo. The handsets are placed in an environmental chamber and are subjected to severe temperature and humidity conditions to test their reliability. Depending on the manufacturer's test specification, the handset may be powered on or powered off during the test. From these tests, the reliability and lifetime of the cell phone can be estimated.

A typical lifetime test system includes a communication analyzer, power supplies, a handset controller, audio test instruments, and a DMM. A switching system makes the necessary connections between the various test instruments and the handsets.

Switching Configurations

Figure 7-26 is an overview of a cell phone lifetime test system based on Keithley's System 46 Microwave/RF Switch System. Given that this system must be able to switch RF signals, audio signals, and DC signals, a variety of switch cards are required.
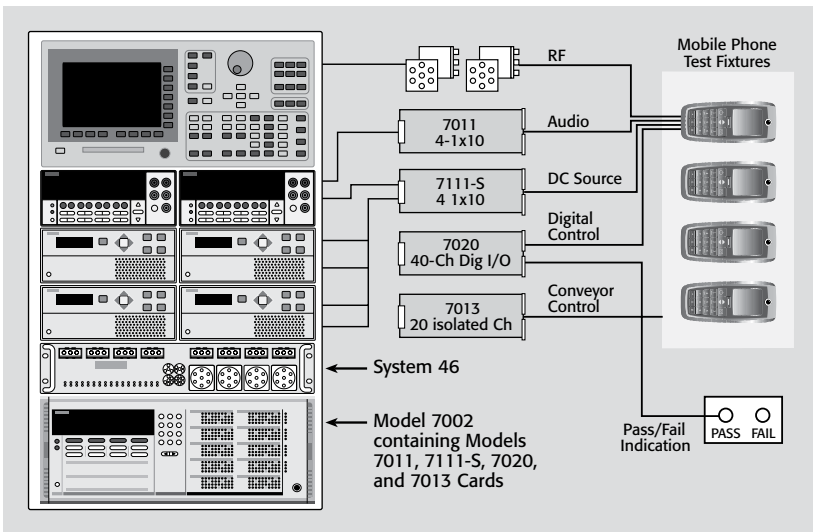
Figure 7-26. Cell phone test system

In this example, high frequency switches are required to connect the communications analyzer to the handset. Therefore, the RF carrier signal is routed by coaxial relays in the System 46 chassis.

A Model 7011 Quad 1×10 Multiplexer Card routes the 20Hz to 20kHz signals used for the audio testing to and from the handset. For testing the audio quality of the handset, a Model 2015 or 2016 Total Harmonic Distortion (THD) Multimeter allows making quick measurements of a variety of parameters, such as THD, THD plus noise, and signal-to-noise plus distortion (SINAD).

The handset under test is powered by the Model 2306 Battery/Charger Simulator; power is routed to the handsets by the Model 7053 High Current Switch Card. This card, which has 10 channels and can carry up to 5A, can easily handle the high current transients that may flow when the phone is switched from receive mode to transmit mode.

A Model 7020 Digital I/O Interface Card is employed to switch the digital signals used to set the phone to various operating modes during testing. This card provides 40 independent inputs and outputs, so it can be used to control many handsets at once.

Isolated relays, such as those used in the Model 7013 Relay Switch Card, can be used to control certain test system requirements, such as the conveyor.

## 7.12 VCSEL Testing with Trigger Synchronized SourceMeter Instruments

Vertical-cavity surface-emitting lasers (VCSEL) are slowly replacing traditional edge-emitting lasers, most notably in low-bandwidth and short-haul communication systems in which cost is a driving factor. Edge-emitting lasers must be cut from the wafer and edges polished before testing is possible, but VCSEL manufacturers can test their devices at the wafer level.

The light intensity (L) current (I) voltage (V) sweep is a series of measurements performed on VCSELs to determine their operating characteristics. The LIV test involves ramping current through the VCSEL and measuring the resulting light output with a photodetector (PD).

Figure 7-27 illustrates a simple test system at the wafer level. Two Model 2602 System SourceMeter instruments are used. A wafer probe makes the electrical connection to each device through a probe card. The prober station also positions the optical detector directly over the devices. When the light from the VCSEL shines on the reverse-biased PD, the leakage current increases. The magnitude of the leakage current correlates to the intensity of the light striking the active region.
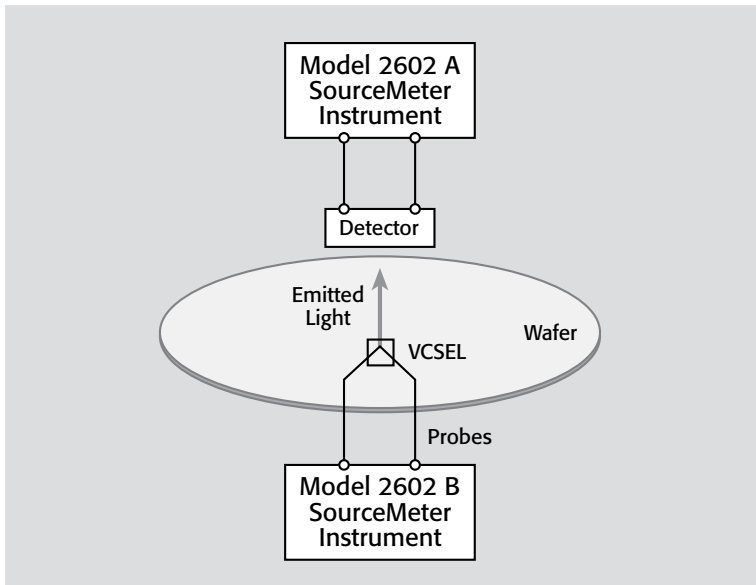
Figure 7-27. Wafer level testing of VCSELs
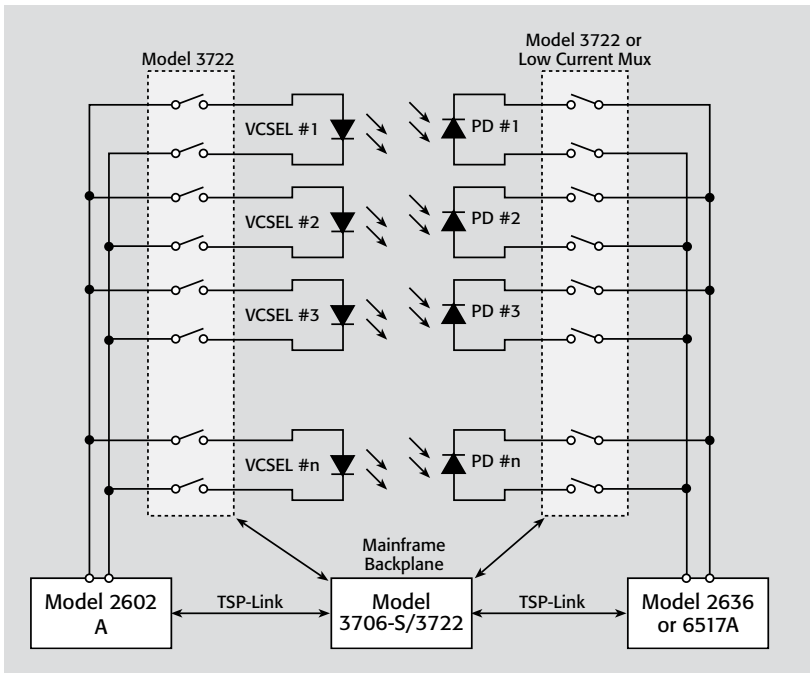
Figure 7-28. Testing multiple VCSELs

Switching Configuration

If the probe card can connect to many devices simultaneously, then a system similar to **Figure 7-28** can be constructed to test all of the devices each time the probe card makes contact with the wafer.

An individual VCSEL is selected for testing and the corresponding relays are closed for the VCSEL and the PD used to verify the light intensity. The Source-Meter instrument first performs the necessary DC tests, such as forward voltage, reverse breakdown voltage, and leakage current. Then it forces sufficient current to light the VCSEL and channel B of the Model 2602 measures the increased leakage of the PD. Once this testing process is complete, switching channels for the next device are selected.

Measuring the PDs can be done with either a Model 2602 or 2636, depending on the current sensitivity required by the test specification. The Model 2602 is useful for measuring currents to approximately 100pA, while the Model 2636 reliably measures currents less than 10fA.

The offset current specification for the Model 3722 Multiplexer Card is <100pA, which may exceed the error budget for the test system. Substituting a Model 7158 Low Current Scanner Card will lower the offset value to <1pA. Note that using a low current card will decrease the number of available channels in the system, since the low current cards only have ten channels for scanning.

7.13 Burn-In Testing for Switching Power Supplies

Switching power supplies are commonly used in telecommunications, desktop computing, and network server hardware; although these supplies are relatively inexpensive, they must be tested rigorously and carefully to maintain a high level of product quality.

Highly accelerated stress screening (HASS) or "burn in" is a common production step for switching power supplies. Extended environmental test is performed to ensure the supplies continue to function properly over the course of their lives. Typically, manufacturers age and monitor thousands of power supplies at once. Perhaps the most significant challenge involved in designing this type of test system is dealing with the high number of channels the system must monitor simultaneously.

Several parameters are typically measured as part of power supply testing, particularly output voltage and temperature. Although the output voltage of a switching power supply may be anywhere from 3V to 48V, the most common output voltages are 5V, 12V, and 15V, and the outputs are usually bipolar. A single switching supply could have as many as six outputs. Obviously, testing multiple switching supplies at once could involve monitoring hundreds of channels. But for purposes of burn-in, only one output is monitored to reduce the huge number of channels.

Temperature measurement during burn-in usually entails monitoring the temperature of the supply, several points in and around the supply, and the general ambient temperature.

The Model 3706 System Switch/Multimeter integrates a 7½-digit multimeter in a single switch matrix enclosure with six rear-panel slots for switching cards, providing an all-in-one switch/read system. This tight integration simplifies switching, measurement, and programming. For burn-in applications, the Model 3706's DMM can be used to measure voltage and temperature, while the switch system can be configured with the appropriate switch cards to accommodate up to several hundred channels. The Model 3720 dual 1×30 multiplexer card with automatic CJC for thermocouples is ideal for the voltage and temperature
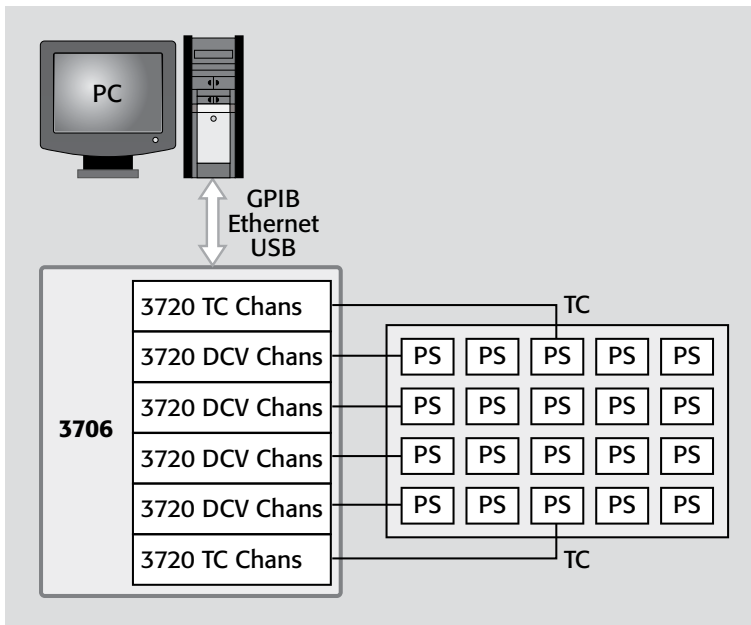
Figure 7-29. Power supply burn-in system with 3706-S System Switch/ Multimeter

measurements required for power supply burn-in applications. **Figure 7-29** illustrates a power supply burn-in test system based on the Model 3706 and multiple Model 3720 cards.

This system can assign a measurement function to each channel. As **Figure 7-29** shows, channels 1–60 are all dedicated to thermocouples (TCs), channels 61 through 300 handle DC voltage measurements, and channels 301 to 360, on the last card, are also dedicated to TCs. The Model 3706, when configured with the Model 3720 switch cards, allows switching and measuring up to 120 channels per second. A system configured with one Model 3706 and six Model 3720 can monitor up to 360 channels every few seconds.

For settings with several test system/stations located throughout the manufacturing area, when two or more systems are used simultaneously, the Model 3706's LXI Class B compliance offers a variety of advantages. The operation of each system can be tightly synchronized and the data uploaded to the manufacturing facility' central computer through the LAN/Ethernet interface for analysis and processing. Features include a 10/100M Base-T Ethernet connection, graphical Web server, LAN-based instrument triggering, and IEEE-1588 precision time

protocol (PTP) synchronization. This synchronization technique provides a standard method to synchronize devices on an Ethernet network with microsecond precision for time/event-based programming.

APPENDIX A

Glossary

The following terms are defined to clarify or expand on how they relate specifically to the material in this handbook.

ACTUATION TIME. The time between application of the nominal relay coil voltage and the final closure of the relay contacts after the contact bounce interval.

AUTOMATIC CJC (COLD JUNCTION COMPENSATION). A system for multi-channel thermocouple measurements where the temperature at each thermocouple/switch card junction is sensed and compensated for automatically.

BANDWIDTH. The range of frequencies that can be switched, conducted, or amplified within certain limits. Under given load conditions, bandwidth is defined by the −3dB (half-power) points.

BANK. A group of relays with a common connection for scanning or multiplex applications.

BLOCKING. A multiplexer of matrix arrangement of relays where only one signal path is active at any given time. Common in RF/microwave testing to maintain the characteristic impedance of the test system.

BREAK-BEFORE-MAKE. Disconnecting the present circuit before connecting a new circuit. Also known as **BREAK/MAKE**.

CARRY CURRENT. The maximum continuous current of closed relay contacts. Most relays are rated higher for carry current than switched current. (Heat is generated by I^2R losses for carry current and I^2R losses plus arcing for switched current.)

CHANNEL. One of several signal paths on a switching card. For scanner (or multiplex) cards, the channel is used as a switched input in measuring circuits or as a switched output in sourcing circuits. For switch cards, each channel's signal paths are independent of other channels.

CHANNEL CROSSTALK. Coupling of a signal from one channel to another or to the output by stray capacitance, inductive coupling, or radiation. Crosstalk is expressed in decibels at a specified load impedance and at a specific frequency.

CHANNEL ISOLATION. On a switching card, the isolation from signal HI and LO of one channel to signal HI and LO of any other channel (or the output on switch or scanner cards). Specified as resistance and capacitance, except for RF cards (decibels and frequency range).

COAXIAL CABLE. A two-conductor cable that has a center conductor surrounded by a shield conductor, the two being coaxial and separated by an insulator.

COIL RESISTANCE. A nominal value of the resistance of the coil winding of a relay.

COLD JUNCTION. The junction in a thermocouple circuit that is at a known temperature. Also known as REFERENCE JUNCTION.

COLD SWITCHING. Closing the relay contacts before applying voltage and current and removing voltage and current before opening the contacts. (Contacts do not make or break current.)

COLUMN. As viewed on the schematic of a matrix card/module, the vertical signal lines that are connected via relays to the horizontal rows.

COMMON MODE. Between two signal lines and a third line (e.g., from signal HI and LO to chassis ground or guard).

COMMON MODE ISOLATION. On a switching card/module, the isolation from signal HI and LO to guard (or shield) for a 3pole circuit, or from signal HI and LO to chassis ground for a two-pole circuit. Specified as resistance and capacitance.

COMMON MODE REJECTION RATIO. The ability of an instrument to reject interference from a common mode voltage at its input terminals with respect to ground. Usually expressed in decibels at a frequency.

COMMON MODE VOLTAGE. A voltage between input low and chassis ground of an instrument.

CONTACT BOUNCE. The intermittent and undesired opening of relay contacts during closure.

CONTACT LIFE. The maximum number of expected closures before failure. Life is dependent on the switched voltage, current, and power. Failure usually occurs when the contact resistance exceeds the end of life value.

CONTACT POTENTIAL. A voltage produced between contact terminals due to the temperature gradient across the relay contacts, and the reed-to-terminal junctions of dissimilar metals. (The temperature gradient is typically caused by the power dissipated by the energized relay coil.)

CONTACT RATING. The voltage, current, and power capacities of relay contacts under specified environmental conditions. *See* CARRY CURRENT *and* SWITCHED CURRENT.

CONTACT RESISTANCE. For a relay, the resistance in ohms across closed contacts. For a Keithley switching card/module, also includes the tape resistance and connector terminal resistance.

Contacts. The surfaces of current carrying elements where electric circuits are opened or closed.

Crosspoint. The intersecting point of a column and row in a relay matrix. Specified as (column, row) or (row, column).

Crosstalk. *See* **Channel Crosstalk**.

Current Surge Limiting. The circuitry necessary to protect relay contacts from excessive transient current.

Differential Input Isolation. On a switching card, the isolation from signal HI to LO. Specified as resistance and capacitance.

Differential Multiplexer. A type of switching card/module where one input is routed to one of several outputs (e.g., sourcing) or one of several inputs is routed to one output (e.g., measuring), and each channel uses a two-pole relay configuration (one pole for signal HI and one pole for signal LO).

Digital I/O. A TTL-level input/output port that is programmable by the mainframe.

Dry Circuit Switching. Switching below specified levels of voltage (e.g., 20mV) and current to minimize any physical and electrical changes in the contact junction.

Dry Reed Relay. A glass-enclosed, hermetically sealed, magnetically actuated contact. No mercury or other wetting material is used.

DUT. An abbreviation for *Device Under Test*.

Electrochemical Effects. The property that generates current between circuit board conductors due to contamination of the card surface. Minimized with proper handling and cleaning.

Electromechanical Relay. A relay that uses an electromagnet to move an armature and make or break the relay contacts.

EMI. Abbreviation for *Electromagnetic Interference*. A term that defines unwanted electromagnetic radiation from a device that could interfere with desired signals in test or communication equipment, for example. RFI (**Radio Frequency Interference**) and EMI are often used interchangeably.

Floating. The condition where a common mode voltage exists between earth ground and the instrument or circuit of interest. (Low of circuit is not at earth potential.) The condition where signal LO in the system is electrically isolated from earth ground.

Form A. A single-pole, normally open contact configuration. Also called **SPST-NO**. A two-pole configuration is called **2 Form A**.

Form B. A single-pole, normally closed contact configuration. Also called **SPST-NC**. A two-pole configuration is called **2 Form B**.

Form C. A single-pole, double-throw contact configuration. Also known as a **Transfer Switch**. A two-pole configuration is called **2 Form C** or DPDT.

Guarding. A technique that reduces leakage errors and decreases response time. Consists of a guard conductor driven by a low-impedance source surrounding the lead of a high-impedance signal. The guard voltage is kept at or near the potential of the signal.

Hot Switching. Opening and closing relay contacts while voltage and current are applied. (Contacts make or break current.) Degrades contact life. Typically used for digital signal switching to prevent state changes.

Impedance Matching. To optimize power transfer and minimize measurement uncertainty in RF/microwave systems, the ohmic values of source, switch, and measure components are equalized, commonly to 50Ω. Differences in impedances cause reflection of the signal.

Independent Switch Card/Module. A type of card where each channel is electrically isolated from all other channels. Also called **Isolated Switch Card/Module**.

Input Isolation. On a switching card, the isolation from signal HI to LO (or guard) for a two-pole circuit. Specified as resistance and capacitance.

Insertion Loss. The attenuation of signals being routed through a switching card. Specified as a decibel value over a frequency range. Becomes more important with low signal levels or high noise levels.

Insulation Resistance. The ohmic resistance of insulation. It degrades quickly as humidity increases.

I/O. Abbreviation for input/output, which refers to the transmission of information to an external device (output), and the reception of information from an external device (input).

Isolated Switch. A type of card where each channel is electrically isolated from all other channels. Also called **Independent Switch Card/Module**.

Isolation. On a switching card/module, the impedance between any stated terminals. Specified as resistance and capacitance. In RF/microwave switching, the ratio of

the power level between adjacent channels, which is expressed in decibels over a frequency range. *See* **Input Isolation**.

Isothermal Block. The thermally conductive block that equalizes the temperature of all thermocouple connections.

Latching Relay. A relay that maintains its contacts in the last position assumed without the need to keep the coil energized.

Leakage Current. Error current that flows through insulation resistance when a voltage is applied.

Low Noise Cable. A cable that is coated with a conductive layer between the braid and inner insulator (coax and triax) and under the inner shield (triax). This reduces triboelectric currents caused by friction due to vibration, movement, or temperature fluctuation.

Mainframe. A switching instrument that operates according to user commands to connect signals among sourcing and measuring instruments and devices under test. Signal switching is performed on cards that are inserted into the mainframe rack. A mainframe is also referred to as a **Scanner**, **Multiplexer**, **Matrix**, or **Programmable Switch**.

Make-Before-Break. Connecting a new circuit before disconnecting the present circuit. Also known as **Make/Break**.

Matrix. Connecting multiple inputs to multiple outputs.

Matrix Card/Module. A type of card with a switching configuration that has columns and rows of relay crosspoints. With a matrix card, since any one point can be connected to any other, you can simultaneously have one input with multiple outputs, multiple inputs with one output, or multiple inputs with multiple outputs.

Mercury Wetted Relay. A reed relay in which the contacts are wetted by a film of mercury. Usually has a required position for proper operation; some types are position insensitive.

Module. *See* **Switch Cards/Modules**.

Multiplex. Connecting one instrument to multiple devices under test or multiple instruments to one device under test. *Also see* **Scan**.

Multiplex Card. *See* **Scanner Card**.

Noise. An undesirable electrical signal from an external source (such as an AC power line, motors, generators, transformers, fluorescent lights, CRT displays, computers, radio transmitters, and others) that is imposed on a desired signal.

Non-blocking. A multiplexer or matrix arrangement of relays where it is possible to switch any signal to any DUT at any time. It has high flexibility and high cost.

Non-latching Relay. A relay that maintains its closed contact position when the coil is energized and its open contact position when the coil is not energized.

Normally Closed Contacts. A contact pair that is closed when the relay is not energized.

Normally Open Contacts. A contact pair that is open when the relay is not energized.

Normal Mode. Between two signal lines (e.g., from signal HI to signal LO).

Normal Mode Rejection Ratio. The ability of an instrument to reject an AC interference (usually of line frequency) across its input terminals. Usually expressed in decibels at a frequency.

Normal Mode Voltage. A voltage applied between the input high and input low terminals of an instrument.

Offset Current. A current that comes from a switching card even though no signals are applied. It comes mostly from the finite coil-to-contact impedance. It is also generated by triboelectric, piezoelectric, and electrochemical effects present on the card.

Path Isolation. On a matrix switching card, the isolation from signal HI and LO of one path to signal HI and LO of any other path. Specified as resistance and capacitance.

Path Resistance. On a matrix switching card, the resistance per conductor of a closed path, including the contact resistance, wiring resistance, and connector terminal resistance.

Phase Distortion. The shifting of RF/microwave or digital waveforms due to signal paths of different lengths and different propagation delays through test systems. May cause errors in digital testing.

Piezoelectric Currents. The current caused by mechanical stress to certain insulating materials. To minimize, the stress is removed from the insulators, and materials with low piezoelectric effect are used.

POLE. A set of mating contacts in a relay or switch: normally open, normally closed, or both.

PROPAGATION DELAY. The specified amount of time for a signal to be routed through a previously closed channel of a switching card. The delay must be considered, for example, when the switched signal is used to synchronize other signals.

REED RELAY. A relay using one or more glass-enclosed, hermetically sealed, magnetically actuated contact members. Some types are dry to improve isolation or make them position independent. Some types are mercury wetted to improve switched current rating and make contact resistance more predictable. *Also see* **ELECTROMECHANICAL RELAY** *and* **SOLID STATE RELAY**.

REFERENCE CHANNEL. On a thermocouple scanner card, the channel that measures the temperature of the isothermal block.

REFERENCE OUTPUT. The output signal representing the temperature of the reference channel, usually the isothermal block, on some thermocouple scanner cards/modules.

RELAY. An electrically controlled mechanical device that opens and closes an electrical contact. A relay provides isolation of control signals from switched signals.

RELAY DRIVE. The total current available from the power supply of the mainframe to energize the relay coils on switching cards. This current is derated at elevated temperatures.

RELAY DRIVE CURRENT. The amount of current necessary to energize a relay. Usually specified per channel.

RELAY SETUP. A configuration of open and closed relays.

RELEASE TIME. The time between the removal of the coil voltage and the stabilized opening of the contacts.

RETURN LOSS. A measure of the power reflected back towards the source due to an impedance mismatch among the source, transmission line, and the load. Expressed in dB.

ROW. As viewed on the schematic of a matrix card/module, the horizontal signal lines that are connected via relays to the vertical columns.

SCAN. Sequential connecting (usually break-before-make) of one instrument to multiple devices under test or multiple instruments to one device under test. *Also see* **MULTIPLEX**.

SCANNER. *See* **MAINFRAME**.

SCANNER CARD. A type of switching card where one input is routed to one of several outputs (e.g., sourcing), or one of several inputs is routed to one output (e.g., measuring). The actual switching can be nonsequential (multiplex) or sequential (scan). Also known as a **MULTIPLEX CARD**.

SETTLE TIME. The time required for establishing relay connections and stabilizing user circuits.

SHIELDING. A metal enclosure for the circuit being measured or a metal sleeving surrounding wire conductors (coax or triax cable) to reduce electrostatic interference. The shield is usually connected to the LO terminal of the sensitive instrument..

SINGLE-ENDED MULTIPLEXER. A type of switching card/module where one input is routed to one of several outputs (e.g., sourcing) or one of several inputs is routed to one output (e.g., measuring). Each channel uses a single-pole relay for signal HI and a single common terminal is connected to signal LO for all channels.

SOLID STATE RELAY. A relay that switches electric circuits by use of semiconductor elements without moving parts or conventional contacts.

SMA. A type of miniature coaxial connector used in situations requiring shielded cable for signal connections.

SMB. A type of miniature coaxial connector used in situations requiring shielded cable for signal connections.

SWITCH/MEASURE SYSTEM. An instrument that integrates a switch mainframe and a digital meter into a single chassis. Signal switching is performed on cards/modules that are inserted into the chassis.

SWITCHED CURRENT. The maximum current level that can be reliably handled while opening and closing contacts. *Also see* **CARRY CURRENT**.

SWITCHING CARD/MODULES. The general classification of relay cards. May be subdivided into: independent switch cards (1 input to 1 output), scanner or multiplex cards (1:N, N:1) and matrix cards (M:N).

T/C COLD JUNCTION. *See* **COLD JUNCTION.**

TEST FIXTURE. An enclosure, sometimes shielded, used for mounting single or multiple devices for testing purposes.

THERMAL OFFSET VOLTAGE. *See* **CONTACT POTENTIAL**.

Triaxial Cable. A three-conductor cable that has a center conductor surrounded by an inner shield conductor that is in turn surrounded by an outer shield conductor.

Triboelectric Current. The current caused by friction between a conductor and insulator when a cable flexes due to vibrations, movement, or temperature fluctuation. *Also see* **Low Noise Cable**.

Trigger. An external stimulus that initiates one or more instrument functions. Trigger stimuli include: the front panel, an external trigger pulse, and IEEE-488 bus X, Talk, and GET triggers.

TSP. Test Script Processor. An onboard processor, used in a growing number of Keithley instruments and switch mainframes, designed for executing test scripts within the instrument. Using TSP test scripts instead of a PC for instrument control avoids communication delays between the PC controller and instrument, allowing improved test throughput. Test scripts can contain math and decision-making rules that further reduce the interaction between a host PC and the instrument.

TSP-Link. The TSP-Link master/slave connection offers easy system expansion between Keithley's Series 3700 mainframes. TSP-Link can also be used to connect to other TSP-Link enabled instruments, such as Series 2600 System SourceMeter instruments. All instrumentation connected via TSP-Link can be controlled by the master unit, just as if they were all housed in the same chassis.

Voltage Clamping. The circuitry necessary to protect relay contacts from excessive voltage caused by switching current into inductive loads.

VSWR. Abbreviation for **Voltage Standing Wave Ratio**. A measure of signal reflection along a transmission line. Expressed as a ratio of the highest voltage to the lowest voltage found along the signal path.

For further reading on switching terminology, see the following references:

ANSI/EIA RS-473-1981. Definitions and Terminology for Relays for Electronic Equipment. American National Standards Institute, 1981.

ANSI/IEEE Std. 100-1992. IEEE Standard Dictionary of Electrical and Electronics Terms. 5th edition. Institute of Electrical and Electronics Engineers, 1992.

Engineers' Relay Handbook. 5th edition. Relay and Switch Industry Association (formerly National Association of Relay Manufacturers), 1996.

APPENDIX B

Switch Card and Switch Module Selector Guides

Switching Cards for Series 3700 Mainframes*

Card	No. of Channels	Card Config.	Type of Relay	Contact Configuration	
3720	60 (Dual 1×30)	Multiplexer	Latching electromechanical	2 form A	
3721	40 (dual 1×20)	Multiplexer	Latching electromechanical	2 form A	
3722	96 (dual 1×48)	Multiplexer	Latching electromechanical	2 form A	
3723	60 (dual 1×30) or 120 single pole (dual 1×60)	Multiplexer	Dry reed	1 form A	
3730	6×16	Matrix	Latching electromechanical	2 form A	
3740	32	Independent	Latching electromechanical	28 form C, 4 form A	

*Additional Series 3700 switching cards are currently in development. Consult www.keithley.com for information on new cards as they are released.

Max. Voltage	Max. Current Switched	Comments
300 V	1 A	2 independent 1×30 multiplexers. Automatic temperature reference with screw terminal accessory (Model 3720-ST)
300 V (ch 1–40), 60 V (ch 41–42)	2 A (ch 1–40), 3 A (ch 41–42)	2 independent 1×20 multiplexers. Automatic temperature reference with screw terminal accessory (Model 3721-ST)
300 V	1 A	2 independent 1×48 multiplexers
200 V	1 A	2 independent 1×30 multiplexers
300 V	1 A	Columns can be expanded through the backplane or isolated by relays
300 VDC/250 VAC (Form A)	2 A (Form C), 7 A (Form A)	32 general purpose independent channels.

Switching Cards for 7001 and 7002 Mainframes

	No. of Channels	Card Config.	Contact Config.	Max. Voltage	Max. Current	Max. Power	
HIGH DENSITY							
7011-C	40	Multiplexer	2 form A	110 V	1 A	60 VA	
7011-S	40	Multiplexer	2 form A	110 V	1 A	60 VA	
7012-C	4×10	Matrix	2 form A	110 V	1 A	60 VA	
7012-S	4×10	Matrix	2 form A	110 V	1 A	60 VA	
7013-C	20	Isolated Switch	2 form A	110 V	1 A	60 VA	
7013-S	20	Isolated Switch	2 form A	110 V	1 A	60 VA	
7015-C	40	Multiplexer	2 form A	175 V	34 mA	0.3 VA	
7015-S	40	Multiplexer	2 form A	175 V	34 mA	0.3 VA	
7018-C	28	Multiplexer	3 form A	110 V	1 A	60 VA	
7018-S	28	Multiplexer	3 form A	110 V	1 A	60 VA	
7035	36	Multiplexer	2 form A	60 V	1 A	30 VA	
7036	40	Isolated Switch	1 form A	60 V	1 A	30 VA	
7111-S	40	Multiplexer	1 form C	110 V	1 A	60 VA	
GENERAL PURPOSE							
7166	10	Isolated switch	2 form A	300 V	750mA	30 VA	
LOW VOLTAGE							
7067	10	Multiplexer	4 form A	150 V	350mA	10 VA	
7168	8	Multiplexer	2 form A	10 V	50mA		
HIGH VOLTAGE							
7154	10	Multiplexer	2 form A	1100 V	500mA	10 VA	
7169A	20	Isolated switch	1 form C	500 V	500mA	10 VA	
CONTROL							
7019-C	Dual 3×6	Matrix	1 form A	200 V	1 A	10 VA	
7020 7020-D*	80	Digital I/O					
7021	30/20	Multiplexer/ Digital I/O	2 form A	110 V	1 A	30 VA	
7037-D*	30/20	Isolated/ Digital I/O	1 form A	110 V	1 A	30 VA	
7065							

Contact Potential	Offset Current	Max. Recomm. Frequency	Connection Type	CE	Comments
HIGH DENSITY					
<1 µV	<100 pA	2 MHz	Connector	Yes	Four independent 1×10 multi-plexers, connection to backplane
<500 nV	<100 pA	2 MHz	Screw term.	Yes	Four independent 1×10 multi-plexers, connection to backplane
<1 µV	<100 pA	2 MHz	Connector	Yes	Rows connect to analog backplane
<500 nV	<100 pA	2 MHz	Screw term.	Yes	Rows connect to analog backplane
<1 µV	<100 pA	10 MHz	Connector	Yes	
<500 nV	<100 pA	10 MHz	Screw term.	Yes	
<5 µV	<1nA	500 kHz	Connector	Yes	Solid state switch for high reliability
<5 µV	<1nA	500 kHz	Screw term.	Yes	Solid state switch for high reliability
<5 µV	<100 pA	2 MHz	Connector	Yes	3 pole switching
<5 µV	<100 pA	2 MHz	Screw term.	Yes	3 pole switching
<1 µV	<100 pA	10 MHz	Connector	Yes	9 independent 1×4 multiplexers
<4 µV	<100 pA	10 MHz	Connector	Yes	40 independent channels of one-pole switching
<500 nV	<100 pA	2 MHz	Screw term.	Yes	Four independent 1×10 multi-plexers, connection to backplane
GENERAL PURPOSE					
75 µV typ.		3 MHz	Connector	Yes	Mercury wetted contacts
LOW VOLTAGE					
<1 µV		1 MHz	Screw term.	Yes	4 wire resistance measurements
<30 nV		1 kHz	Screw term.	Yes	
HIGH VOLTAGE					
<35 µV		1 MHz	Screw term.	Yes	
<30 µV		2 MHz	Connector	Yes	Coupon testing. Use with 7002.
CONTROL					
<25 µV	<100 pA	2 MHz	Connector	Yes	6-wire resistance measurements
			Connector	Yes	40 inputs/40 outputs
<3 µV	<100 pA	10 MHz	Connector	Yes	Dual multiplexers. Up to 30 channels, 10 digital inputs, 10 digital outputs.
<4 µV	<100 pA	10 MHz	Connector	Yes	30 independent channels of one-pole switching, 10 digital inputs, 10 digital outputs
					Hall Effect measurement buffer card

Switching Cards for 7001 and 7002 Mainframes (cont.)

	No. of Channels	Card Config.	Contact Config.	Max. Voltage	Max. Current	Max. Power	
LOW CURRENT							
7152	4×5	Matrix	2 form A	200 V	500 mA	10 VA	
7153	4×5	Matrix	2 form A	1300 V	500 mA	10 VA	
7158	10	Multiplexer	1 form C	30 V	100 mA		
HIGH CURRENT							
7053	10	Multiplexer	2 form C	300 V	5 A	100 VA	
RF							
7016A	double 1×4	2 isolated switches	1 pole, 4 throw	30 V	500 mA	10 VA	
7017	double 1×4	2 isolated switches	1 pole, 4 throw	30 V	1 A	10 VA	
7038	12	Three 1×4 multiplexers	1 pole, 1 of 4 tree	24 V	10 mA	10 W @ 1.2 GHz	
THERMOCOUPLE							
7014	39	Multiplexer	2 form A	110 V	1 A	60 VA	

* Cards with a -D suffix feature D-sub connectors.

Card	No. of Channels	Fiber Type	Wavelength (nm)	Connector	Fiber Length
OPTICAL					
7090-8-4	1×4	Multimode fiber 62.5/125 each ch.	780–1350	FC/SPC	1m
7090-16-6	1×4	Single-mode fiber (SMF-28) 9/125 each ch.	1290–1650	FC/SPC	1m

Note: Optical switch cards are configured as single channel, 1×N non-blocking switch.

Switching Cards for 7002-HD Mainframes

	No. of Channels	Card Config.	Contact Config.	Max. Voltage	Max. Current	Max. Power	
HIGH DENSITY							
7002-HD-MUX1	quad 1×40	Multiplexer	2 form A	200 V	1 A	125 VA	
7002-HD-MTX1	6×32	Matrix	2 form A	200 V	1 A	125 VA	

	Contact Potential	Offset Current	Max. Recomm. Frequency	Connection Type	CE	Comments
LOW CURRENT						
	<20 µV	<1 pA	60 MHz	Connector	Yes	
	<50 µV	<1 pA	60 MHz	Connector	Yes	
	<200 µV	<1 pA	1 MHz	BNC	Yes	
HIGH CURRENT						
	<1 mV		1 MHz	Screw term.		
RF						
	<6 µV		2 GHz	SMA	Yes	Optional 50Ω termination
	<25 µV		800 MHz	SMA	Yes	10^8 closures contact life.
	<15 µV		2 GHz	75Ω SMB receptacle	Yes	75Ω characteristic impedance
THERMOCOUPLE						
	<1µV	<100pA	2 MHz	Screw term.	Yes	Built-in cold junction reference

	Contact Potential	Offset Current	Max. Recomm. Frequency	Connection Type	CE	Comments
HIGH DENSITY						
	<4.5 µV	<100 pA	25 MHz	Connector, Screw Term.	Yes	
	<4.5 µV	<100 pA	2 MHz	Connector, Screw Term.	Yes	

Switching Cards for 707A and 708A Mainframes

	No. of Channels	Card Config.	Contact Config.	Max. Voltage	Max. Current	Max. Power	
LOW CURRENT							
7072	8×12	Matrix	2 form A	200 V	1 A	10 VA	
7072-HV	8×12	Matrix	2 form A	1300 V	1 A	10 VA	
7174A	8×12	Matrix	2 form A	200 V	2 A		
GENERAL PURPOSE							
7071	8×12	Matrix	3 form A	200 V	500 mA	10 VA	
7071-4	Dual 4×12	Matrix	3 form A	200 V	500 mA	10 VA	
7075	Eight 1×12	Multiplexer	2 form A	110 V	1 A	30 VA	
HIGH FREQUENCY							
7173-50	4×12	Matrix	2 form C	30 V	0.5 A	10 VA	

Switching Cards for 2000, 2001, 2002, and 2010 Multimeters

	No. of Channels	Card Config.	Contact Config.	Max. Voltage	Max. Current	Max. Power	
GENERAL PURPOSE							
2000-SCAN	10	Multiplexer	2 form A	110 V	1 A	30 VA	
2001-SCAN	10	Multiplexer	2 form A	110V	1 A	30 VA	
THERMOCOUPLE							
2001-TCSCAN	9	Multiplexer	2 form A	110 V	1 A	30 VA	

	Contact Potential	Offset Current	Max. Recomm. Frequency	Connection Type	CE	Comments
LOW CURRENT						
	<20 μV	<1 pA	15 MHz	3-lug triax	Yes	Optimized for semiconductor applications.
	<20 μV	<1 pA	4 MHz	3-lug triax		Optimized for semiconductor applications.
		<100 fA	30 MHz	3-lug triax	Yes	Optimized for semiconductor applications.
GENERAL PURPOSE						
	<5 μV	<100 pA	3 MHz	Connector	Yes	Also provides screw terminal connection.
	<5 μV	<100 pA	3 MHz	Connector	Yes	Screw terminals available on row connections.
	<5 μV	<100 pA	30 MHz	Connector	Yes	
HIGH FREQUENCY						
	<15 μV	<200 pA	200 MHz	BNC	Yes	

	Contact Potential	Connection Type	CE	Comments
GENERAL PURPOSE				
	<1 μV	Screw terminal	Yes	Configurable to four-pole
	<1 μV	Screw terminal	Yes	2001, 2002 only; configurable to four-pole; two high-speed channels
	<1 μV	Screw terminal	Yes	Built-in cold junction reference

Switch/Control Modules for 2700, 2701 and 2750 Multimeter/

Module	# Analog Inputs	Configuration	Differential*	four-pole	Type of Connector	Max. Voltage	
7700	20	Multiplexer w/ CJC	1×20 or two 1×10	1×10	Screw terminals	300 V	
7701	32	Multiplexer	1×32 or two 1×16	1×16	D-sub	150 V	
7702	40	Multiplexer	1×40 or two 1×20	1×20	Screw terminals	300 V	
7703	32	Multiplexer	1×32 or two 1×16	1×16	D-sub	300 V	
7705	40	Independent SPST	N/A	N/A	D-sub	300 V	
7706	20	Multiplexer w/ CJC	1×20 or two 1×10	1×10	Screw terminals	300 V	
7707	10	Multiplexer/ Digital I/O	1×10 or two 1×5	1×5	D-sub	300 V	
7708	40	Multiplexer w/ CJC	1×40 or two 1×20	1×20	Screw terminals	300 V	
7709	48	6×8 Matrix	Yes	Yes	D-sub	300 V	
7710	20	Multiplexer w/ CJC	1×20 or two 1×10	1×10	Screw terminals	60 V	
7711	8	Multiplexer	two 1×4	No	SMA	30 Vrms, 60 VDC	
7712	8	Multiplexer	two 1×4	No	SMA	30 Vrms, 42 VDC	

* Can be disconnected from internal DMM for routing external signals.

Source/Switch Modules for 2790 SourceMeter®

Module	# Analog Inputs	Card Configuration	Current Source	
7751	12	Four 1 form A, plus four four-pole or eight two-pole	0–50 mA	
7752	12	Four 1 form A, plus four four-pole or eight two-pole	0–50 mA	
7753	12	Four 1 form A, plus four four-pole or eight two-pole	0–50 mA	

Switching Cards for 6517A Electrometer/High Resistance Meter

Card	No. of Channels	Card Configuration	Contact Configuration	Max. Voltage	Max. Current	
6521	10	Multiplexer	1 form A for signal HI, common LO	30 V	500 mA	
6522	10	Multiplexer	1 form A for signal HI, common LO	200 V	500 mA	

Data Acquisition/Switch Systems

Max. Switched Current	Current Measurement Channels	Digital I/O	Switch Speed	Other
1 A	2 channels @ 3 A	N/A	3 ms	Maximum power = 125 VA.
1 A	N/A	N/A	3 ms	Maximum power = 125 VA.
1 A	2 channels @ 3 A	N/A	3 ms	Maximum power = 125 VA.
500 mA	N/A	N/A	1 ms	Reed relays.
2 A	N/A	N/A	3 ms	Maximum power = 125 VA.
1 A	N/A	16 Digital Out Only	3 ms	(2) ±12 V analog output channels & 100 kHz event counter/totalizer. Maximum power = 125 VA.
1 A	N/A	32 Digital I/O	3 ms	Maximum power = 125 VA. (4) eight-bit word I/O.
1 A	N/A	N/A	3 ms	Maximum power = 125 VA.
1 A	N/A	N/A	3 ms	Connects to internal DMM. Daisy chain multiple cards for up to a 6×40 matrix. Maximum power = 125 VA.
100 mA	N/A	N/A	0.5 ms	Maximum power = 4.2 VA
0.5 A	N/A	N/A	10 ms	2 GHz, maximum power = 20 W per module
0.5 A	N/A	N/A	10 ms	3.5 GHz, maximum power = 20 W per module

Airbag Test System

Voltage Source	I/V Converter	Current Measure	Contact Potential	Type of Connector	Switch Speed
50–500 V	Yes	0–50 µA	<3 µV	Screw terminals	3 ms
	No		<3 µV	Screw terminals	3 ms
50–500 V	Yes	0–500 µA	<3 µV	Screw terminals	3 ms

Max. Power	Contact Potential	Offset Current	Actuation Time	Connection Type
10VA	<200 µV	<1 pA	2 ms	BNC inputs, triax outputs
10VA	<200 µV	<1 pA	2 ms	Triax inputs and output

APPENDIX C

Safety Considerations

Many electrical test systems or instruments are capable of measuring or sourcing hazardous voltage and power levels. It is also possible, under single fault conditions (e.g., a programming error or an instrument failure), to output hazardous levels even when the system indicates no hazard is present.

These high voltage and power levels make it essential to protect operators from any of these hazards at all times.

Protection methods include:

- Design test fixtures to prevent operator contact with any hazardous circuit.

- Make sure the device under test is fully enclosed to protect the operator from any flying debris.

- Double insulate all electrical connections that an operator could touch. Double insulation ensures the operator is still protected, even if one insulation layer fails.

- Use high-reliability, fail-safe interlock switches to disconnect power sources when a test fixture cover is opened.

- Where possible, use automated handlers so operators do not require access to the inside of the test fixture or have a need to open guards.

- Provide proper training to all users of the system so they understand all potential hazards and know how to protect themselves from injury.

It is the responsibility of the test system designers, integrators, and installers to make sure operator and maintenance personnel protection is in place and effective.

The following safety precautions should be observed before using any Keithley product and any associated instrumentation. Although some instruments and accessories would normally be used with non-hazardous voltages, there are situations where hazardous conditions may be present.

Keithley products are intended for use by qualified personnel who recognize shock hazards and are familiar with the safety precautions required to avoid possible injury. Read and follow all installation, operation, and maintenance information carefully before using the product. Refer to the manual for complete product specifications.

If Keithley products are used in a manner not specified, the protection provided by the products may be impaired.

The types of product users are:

Responsible body is the individual or group responsible for the use and maintenance of equipment, for ensuring that the equipment is operated within its specifications and operating limits, and for ensuring that operators are adequately trained.

Operators use the product for its intended function. They must be trained in electrical safety procedures and proper use of the instrument. They must be protected from electric shock and contact with hazardous live circuits.

Maintenance personnel perform routine procedures on the product to keep it operating properly, for example, setting the line voltage or replacing consumable materials. Maintenance procedures are described in the manual. The procedures explicitly state if the operator may perform them. Otherwise, they should be performed only by service personnel.

Service personnel are trained to work on live circuits, and perform safe installations and repairs of products. Only properly trained service personnel may perform installation and service procedures.

Keithley products are designed for use with electrical signals that are rated Measurement Category I and Measurement Category II, as described in the International Electrotechnical Commission (IEC) Standard IEC 60664. Most measurement, control, and data I/O signals are Measurement Category I and must not be directly connected to mains voltage or to voltage sources with high transient over-voltages. Measurement Category II connections require protection for high transient over-voltages often associated with local AC mains connections. Assume all measurement, control, and data I/O connections are for connection to Category I sources unless otherwise marked or described in the manual.

Exercise extreme caution when a shock hazard is present. Lethal voltage may be present on cable connector jacks or test fixtures. The American National Standards Institute (ANSI) states that a shock hazard exists when voltage levels greater than 30V RMS, 42.4V peak, or 60VDC are present. **A good safety practice is to expect that hazardous voltage is present in any unknown circuit before measuring.**

Operators of Keithley products must be protected from electric shock at all times. The responsible body must ensure that operators are prevented access and/or insulated from every connection point. In some cases, connections must be exposed to potential human contact. Product operators in these circumstances must be trained to protect themselves from the risk of electric shock. If the circuit

is capable of operating at or above 1000 volts, **no conductive part of the circuit may be exposed**.

Do not connect switching cards directly to unlimited power circuits. They are intended to be used with impedance limited sources. **NEVER connect switching cards directly to AC mains, the level of power supplied by an electric utility company.** When connecting sources to switching cards, install protective devices to limit fault current and voltage to the card.

Before operating an instrument, make sure the line cord is connected to a properly grounded power receptacle. Inspect the connecting cables, test leads, and jumpers for possible wear, cracks, or breaks before each use.

When installing equipment where access to the main power cord is restricted, such as rack mounting, a separate main input power disconnect device must be provided, in close proximity to the equipment and within easy reach of the operator.

For maximum safety, do not touch the product, test cables, or any other instruments while power is applied to the circuit under test. ALWAYS remove power from the entire test system and discharge any capacitors before: connecting or disconnecting cables or jumpers, installing or removing switching cards, or making internal changes, such as installing or removing jumpers.

Do not touch any object that could provide a current path to the common side of the circuit under test or power line (earth) ground. Always make measurements with dry hands while standing on a dry, insulated surface capable of withstanding the voltage being measured.

The instrument and accessories must be used in accordance with its specifications and operating instructions or the safety of the equipment may be impaired.

Do not exceed the maximum signal levels of the instruments and accessories, as defined in the specifications and operating information, and as shown on the instrument or test fixture panels, or switching card.

When fuses are used in a product, replace with same type and rating for continued protection against fire hazard.

Chassis connections must only be used as shield connections for measuring circuits, NOT as safety earth ground connections.

If you are using a test fixture, keep the lid closed while power is applied to the device under test. Safe operation requires the use of a lid interlock.

If a ⊕ screw is present, connect it to safety earth ground using the wire recommended in the user documentation.

The ⚠ symbol on an instrument indicates that the user should refer to the operating instructions located in the manual.

The ⚠ symbol on an instrument shows that it can source or measure 1000 volts or more, including the combined effect of normal and common mode voltages. Use standard safety precautions to avoid personal contact with these voltages.

The ⚠ symbol on an instrument shows that the surface might be hot. Avoid personal contact to prevent burns.

The ⏚ symbol indicates a connection terminal to the equipment frame.

The **WARNING** heading in a manual explains dangers that might result in personal injury or death. Always read the associated information very carefully before performing the indicated procedure.

The **CAUTION** heading in a manual explains hazards that could damage the instrument. Such damage may invalidate the warranty.

Instrumentation and accessories shall not be connected to humans.

Before performing any maintenance, disconnect the line cord and all test cables.

To maintain protection from electric shock and fire, replacement components in mains circuits, including the power transformer, test leads, and input jacks, must be purchased from Keithley Instruments. Standard fuses, with applicable national safety approvals, may be used if the rating and type are the same. Other components that are not safety related may be purchased from other suppliers as long as they are equivalent to the original component. (Note that selected parts should be purchased only through Keithley Instruments to maintain accuracy and functionality of the product.) If you are unsure about the applicability of a replacement component, call a Keithley Instruments office for information.

To clean an instrument, use a damp cloth or mild, water based cleaner. Clean the exterior of the instrument only. Do not apply cleaner directly to the instrument or allow liquids to enter or spill on the instrument. Products that consist of a circuit board with no case or chassis (e.g., data acquisition board for installation into a computer) should never require cleaning if handled according to instructions. If the board becomes contaminated and operation is affected, the board should be returned to the factory for proper cleaning/servicing.

SWITCHING HANDBOOK, SIXTH EDITION

A GUIDE TO SIGNAL SWITCHING IN AUTOMATED TEST SYSTEMS

Index

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