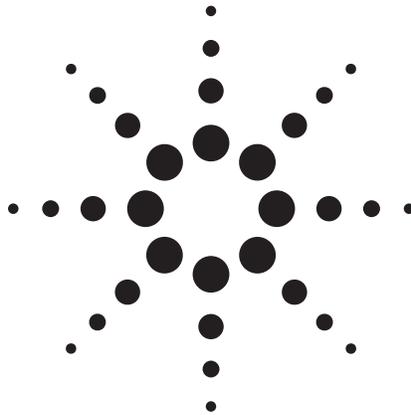


Test System Signal Switching

Application Note 1441-1



Introduction

A switch subsystem may be called upon to switch signals from DC to over 25 GHz, millivolts to thousands of volts, and milliamps to amps. It may even be required to switch optical signals. The loads can be resistive, inductive, capacitive, or a combination of these. The switch subsystem is often expected to automatically supply power to a device under test (DUT), connect specific stimuli to appropriate inputs, connect various points of the DUT to measurement equipment at various times, and then remove power.

With such a wide range of requirements expected of the switch subsystem, it is not surprising that there are many switch topology options. To select the proper topology including the proper type of switch, an engineer naturally must know what is to be tested, how the test is to be conducted, and how often the test or tested device needs to be changed. These test parameters dictate the configuration of the test system, which in turn affects the design of the switch subsystem.

A generic test-system architecture is shown in **Figure 1**, pg.2. The switch is central to the entire system, connecting the many test points to the measuring instruments, routing signals, simulating contact closures, and connecting power to the DUT. The switch also allows a level of automation that can greatly decrease time to test, and reduce the monotony and resulting human error associated with conducting a complete test.

Switches are used for two basic functions: providing control input to a DUT and maintaining interconnection between instruments and test points. The control function is often used to provide the stimuli required to perform a test. For example, switches used to control the automatic seat adjustment in automobiles can be simulated during the test of the microcontroller that controls that function. The control function includes simulating a contact closure with a general-purpose relay switch, or a simulating a logic level (such as a TTL signal from a sensor or other microcontroller) with a digital I/O device.

The purpose of switches' interconnection function is to reduce the cost of creating a test system. Ideally, a separate instrument would exist for each test point, which would provide the highest performance and most accurate measurements. The cost of such an approach is extreme and usually not needed. Using switches reduces the number of test instruments required. From simple tests that require only a few switches to complicated tests needing thousands of switches that require VXI-based solutions, selecting the appropriate switch topology is a critical part of creating a successful test system.

As long as the amplitude and frequency of the test signals are of moderate value, and the measurement accuracy requirements are not stringent, it is reasonably



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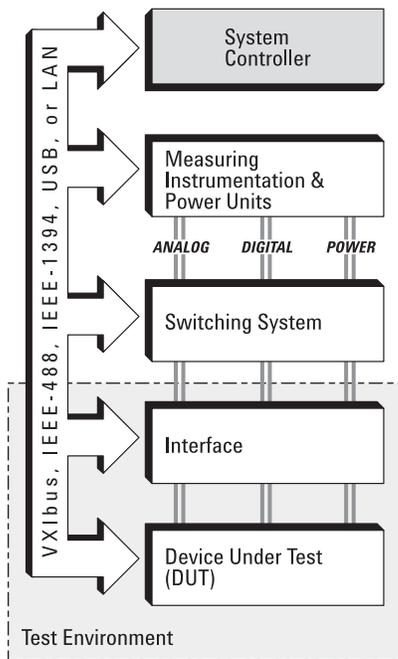


Figure 1.
A generic test-system architecture. Nearly all analog, digital, and power signals pass through the switch subsystem.

easy to construct a switching system from off-the-shelf parts. Potential savings in the cost of hardware obtained by building a custom switching device may be consumed, perhaps many times over, by design time, documentation, and support costs. These costs tend to make the purchase of well-specified commercial hardware attractive.

This application note is for engineers who must create test systems for testing electronic and electromechanical devices. It describes the options available for designing the switching subsystem, including switching topologies and types of switches. It also addresses how to increase reliability and accuracy of the test system through careful switch subsystem design.

Switching Topologies

Switching topologies, distinct from system configurations, involve the actual routing of the test signals as well as the power from the instruments to the DUT. Switching topologies can be divided into three categories based on their complexity: simple relay configurations, multiplexers, and matrices. Which

one to use depends on the number of instruments and test points, whether connections must be simultaneous or not, required test speed, cost considerations, and other testing factors.

A convenient and cost-effective method of creating a switch subsystem is to use a switch mainframe that accepts many different types of modular plug-ins. For example, the Agilent 3499 switch/control mainframe family includes mainframes to hold from 2 to 14 of the 30 available modules. Modules that provide simple relay multiplexing can be combined with modules that switch RF or optical signals.

Simple Relay Configurations

Simple relay configurations can be used in applications from switching power to the DUT to forming a complex topology for measurements. This configuration is used most often for simple on/off switching of power rather than for signals. The most common simple relay configurations are called form A, form B, and form C, as shown in **Figure 2**. These can be linked together to form binary switching networks that guarantee that only one point can be connected to any other point at a time, an important safety consideration. Similarly, these switches can be configured to form measurement buses for the connection of many points to one point at a time.

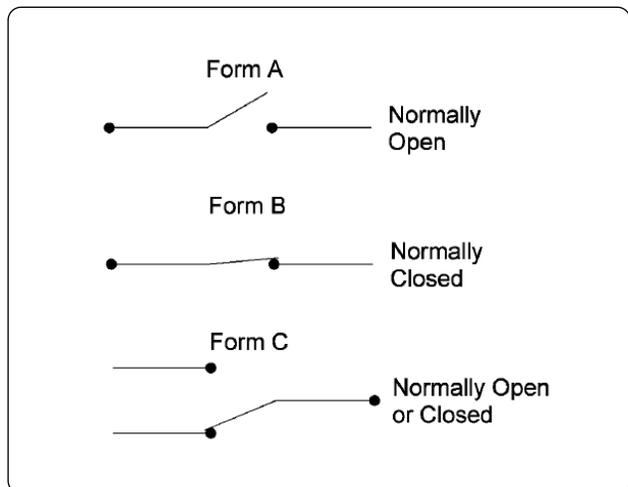


Figure 2. *Simple relay configurations*

A binary switching ladder is depicted in **Figure 3**. These can be used to ensure that only one instrument at a time is connected to a test point, and that no two test points are connected together.

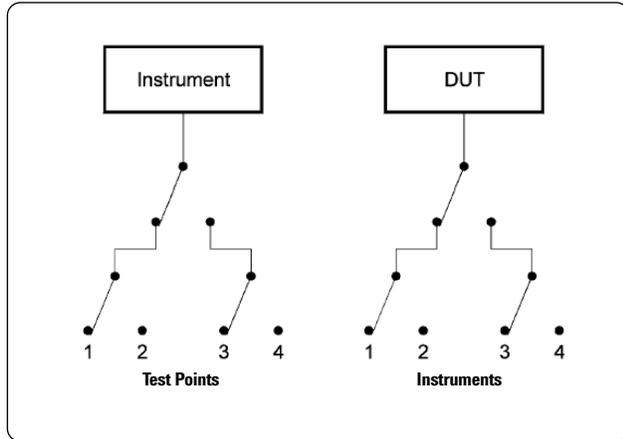


Figure 3. A binary switching ladder using form C relays

Multiplexer Configurations

Multiplexer configurations are most commonly used for signal switching into instrumentation. They are used to connect multiple signals to a single output, such as a number of thermocouples to a voltmeter or a number of test points to an oscilloscope. With this signal switching configuration, only one signal at a time is connected to the measuring device, and the switching is break-before-make (the input is disconnected before a new input is connected). The main advantage of this configuration is economy.

Single-wire configurations (**Figure 4**) are useful for high-frequency applications because most measuring instruments for higher-frequency signals are single

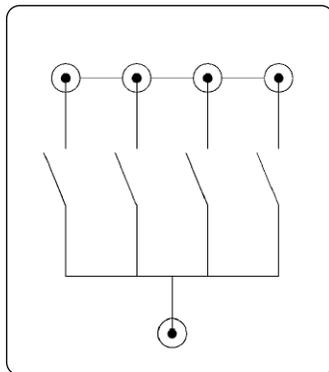


Figure 4. A single-ended multiplexing topology used at higher frequencies. Only the signal conductor is switched; the shield is common to all signals.

ended (common ground or low with all the inputs). Also, at high frequency it is difficult to design a switch where both “high” and “low” are switched without affecting the characteristic impedance through the switch.

Two-wire multiplexers (**Figure 5**) are useful for floating measurements. Inductive coupling can cause the generation of ground loops in the low lead. To break these loops it is necessary to switch the “low” as well as the “high”. This is particularly useful for capacitance and inductance measurements at frequencies below 1 MHz. Devices such as thermocouples and other DC transducers can also be connected to voltmeters with good common-mode noise rejection.

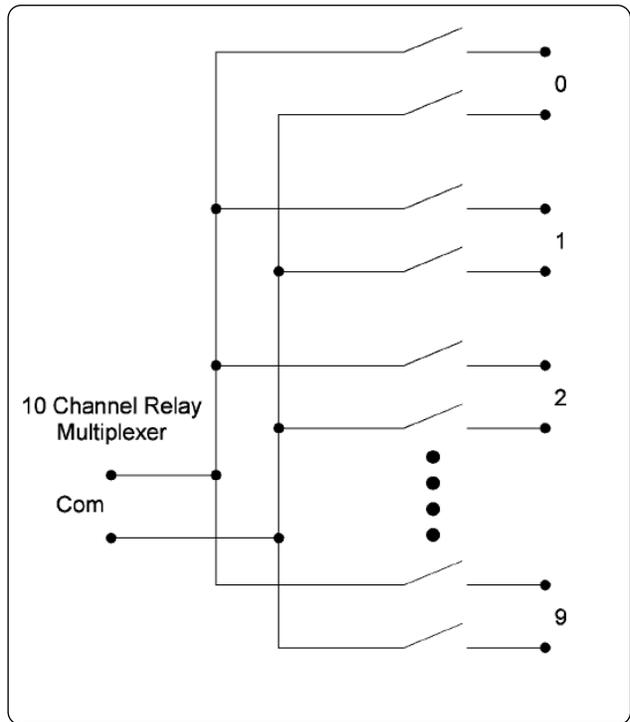


Figure 5. A two-wire multiplexing topology. This 10-channel relay multiplexer can be used for floating measurements because both conductors, the signal and the ground return, are connected to the common bus at the same time.

Three-wire multiplexers are designed for the guarded voltmeter. This additional connection can shunt noise current away from the input measurement terminals and give the user up to 120 dB of common-mode noise rejection, almost 1000 times more than the two-wire measurement. Four-wire multiplexers can be used for four-wire ohm measurements such as resistive bridges. Five- and six-wire switching can be useful for simultaneous application of driven grounds for in-circuit component isolation and measurements.

It is often advisable to select a flexible switch architecture that allows many types of switch topologies. For example, the Agilent N2260A 40-channel multiplexer module (Figure 6) can be configured as an 80-channel 1-wire, 40-channel 2-wire, or 20-channel 4-wire multiplexer.

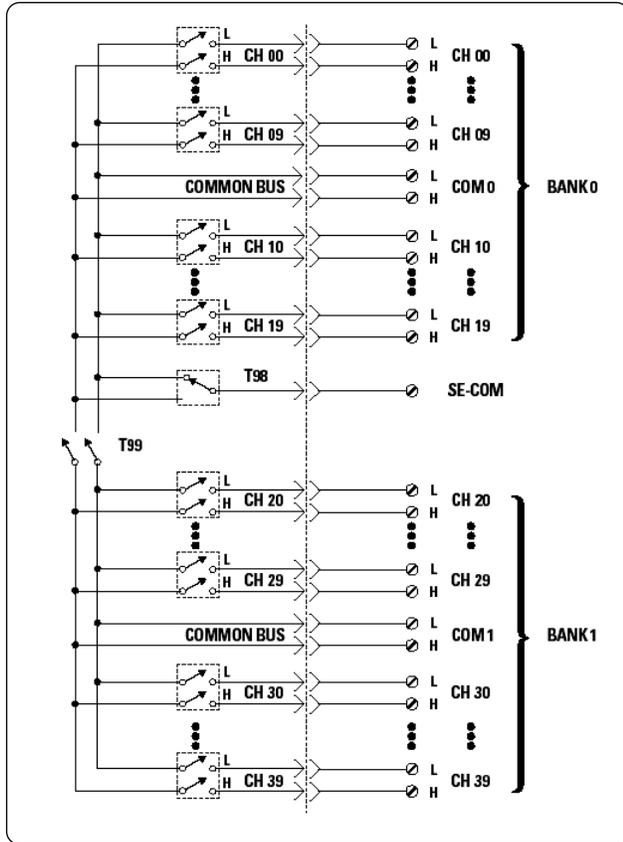


Figure 6. The Agilent N2260A can be configured as an 80-channel 1-wire, 40-channel 2-wire, or 20-channel 4-wire multiplexer.

T-switching is a multiplexer enhancement that reduces unwanted signal coupling into the measurement channels (Figure 7). With T-switching another relay is connected to ground via a low-impedance path, so unwanted signals, which would be capacitively coupled to the measurement, are shunted to ground. This provides excellent channel-to-channel signal isolation at high frequency on the same multiplexer.

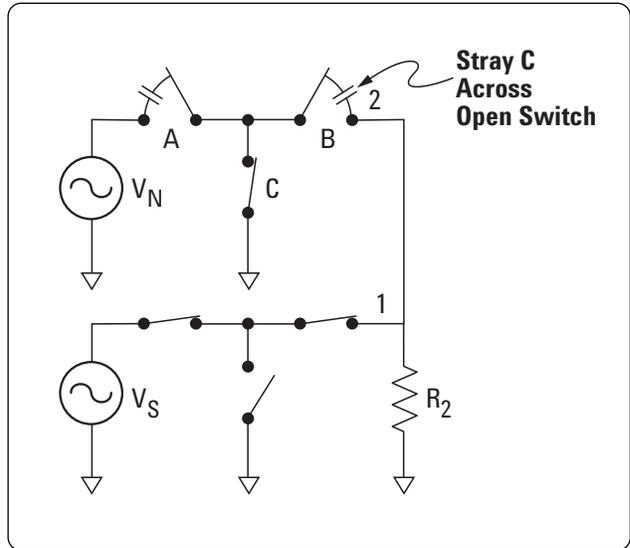


Figure 7. A simplified circuit diagram illustrating T-switching. Conductor 2 is open, so its "C" switch is closed, providing a low-impedance path to ground.

Matrix Configurations

A matrix switch topology is the easiest to specify for any system use and provides extreme flexibility, but for most cases it offers the worst performance for test-system switching. In addition, a matrix configuration, which at a minimum requires at least enough relays to equal the number of inputs times the number of outputs, is generally the most expensive way to approach any test-system switch design. In other words, the tradeoffs are flexibility versus price and performance.

A matrix topology may be required when more than one instrument must be connected to the same test point at the same time. In theory, with a matrix switch topology anything can be connected to anything else in the system simultaneously. **Figure 8** shows the full crossbar matrix of the Agilent N2262A 4 x 8 matrix module. It enables two-wire connection from any point to any point. This configuration can be expanded to much larger systems, but the switch capacitance increases dramatically as the system increases in size.

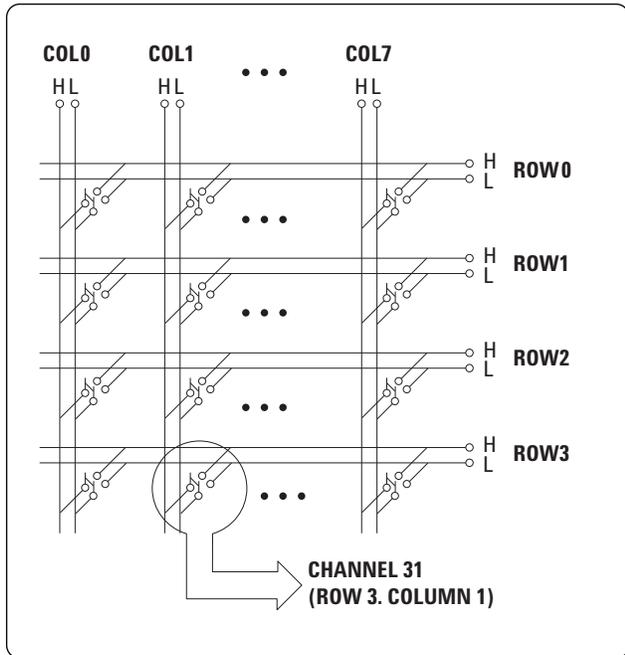


Figure 8. A full crossbar matrix, which allows two-wire connection from any point to any point

Figure 9 shows how multiple matrix cards can be added together to increase the size of a switching system. With five 4 x 4 matrix modules, four instruments can be simultaneously connected to any of 20 test points. Because the interchannel capacitance has increased due to longer conductor paths, the overall capacitance increases more than just the sum of the additional switch capacitances. This makes high-frequency signal integrity difficult to maintain for large matrix configurations.

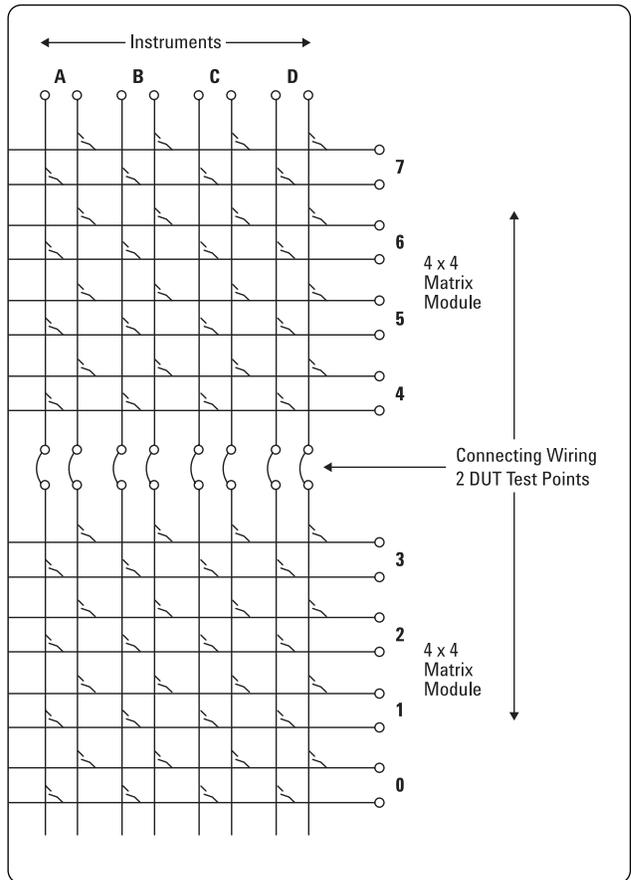


Figure 9. An example of connecting multiple matrix cards together to increase the size of the switching system

Matrix topologies do have a number of drawbacks, including safety, cost, and signal integrity concerns. Because a matrix topology enables a user to connect any point to any other point in the system, there is a greater burden on the test-system designer to create software that prevents the user from connecting components that shouldn't be connected. In a hardware failure, the potential for such a catastrophe is much greater.

The cost of relays, multiplied many times, must be considered when designing a matrix switching system. To switch n items to m items would require at least n times m relays to provide fully arbitrary connections.

Signal integrity is a significant problem in a matrix switch topology. It is very difficult to maintain crosstalk isolation, adequate insertion loss, and good VSWR, so bandwidth is typically reduced in a matrix configuration when compared to a multiplexed configuration for the same type of switches and cabling. Further, there is generally a limitation on the amount of voltage and current switched through the system because of the physical density of the switches in a matrix configuration.

Reflections can be a problem above a few megahertz in frequency. In particular, digital systems can have many reflection and isolation problems that may go undetected because of the relatively low repetition rates coupled with fast transition times on digital signals. Reflections caused by impedance mismatches on the open channels can cause interference with the DUT, and can also result in poor measurements.

With all the problems of a full crossbar matrix, it should be avoided unless complete and arbitrary connections are absolutely necessary. Most test systems do not require simultaneous closure of more than a few channels to individual instruments or test points for complete testing. In most cases a full crossbar matrix can be dodged by judicious selection of multiple multiplexing schemes.

Only limited matrixing is required in most test applications, as when a limited number of signals must be connected to a fixed set of instrumentation simultaneously. However, there is seldom a need to connect all

of these instruments together to the same signal. With matrixed multiplexers, the number of relays needed is reduced from $n \times m$ to $(n \times p) + (m \times p)$, where p is the number of paths between the instruments and the DUT, and n and m are the number of rows and columns in the matrix.

Figure 10 shows how multiplexers can be used to effectively expand the number of inputs or outputs of a matrix. This arrangement is not a true complete crossbar matrix because any combination of inputs cannot be connected to any combination of outputs. For example, channel A cannot be connected to channel 2 while channel C is connected to channel 1. But this “4 x 40” topology can be an economical way to provide flexible multiple channel closures for four different signals.

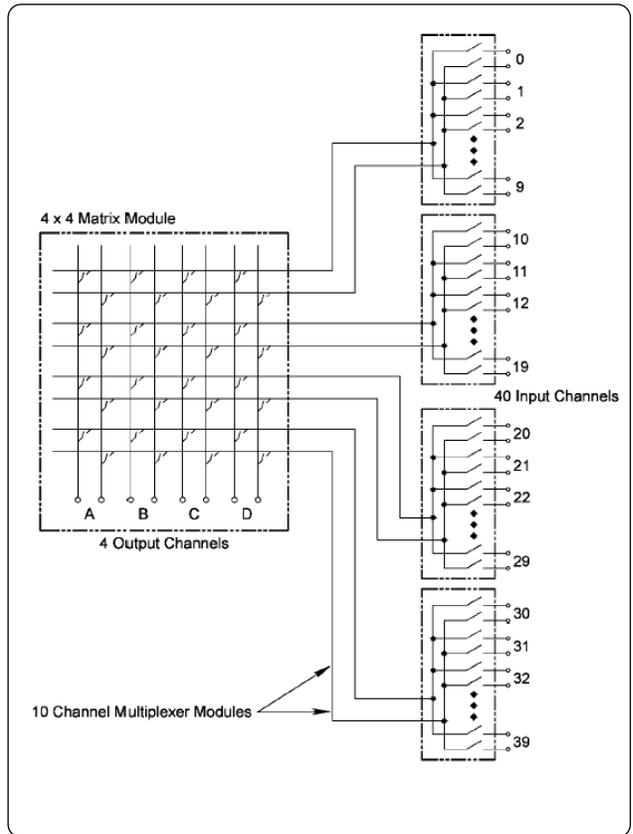


Figure 10. *Multiplexers can be used to effectively and economically expand the number of inputs or outputs of a matrix, although this switching topology does not have the unlimited flexibility of a full crossbar matrix.*

Switch Selection

Besides selection of the switch topology, switch system design also includes selection of the switch type to implement that topology, based on required speed, voltage, and other considerations. The tradeoff between solid-state and mechanical relays is complex. For low-level measurements, the electromechanical relay provides the best overall performance. If speed or the number of switch closures in a controlled environment is important, then the FET switch offers a better solution. However, an FET typically will change the input impedance of the signal to the measuring instrument from a low impedance to a moderately high impedance, which can be a source of error.

Selecting the appropriate relay is also important for maximizing the useful life of the relays. Most electro-mechanical relays are driven electromagnetically. A magnetic flux is generated by passing current through a coil. This magnetic flux causes an armature to move, and the movement causes isolated electrical contacts to open or close, thus making or breaking electrical connections. As with all mechanical devices, relays eventually wear out. However, if the right relays are selected for the type of measurements they are being used for, they will last longer.

Four types of relays are commonly used in switching and signal routing: reed relays, mercury-wetted relays, armature relays, and solid-state relays. Each offers distinct advantages and disadvantages, and each works best for certain applications.

Reed relays, used in the Agilent N2266A 40-channel high-speed multiplexer module, are usually a good choice for switching at high speeds. In general, reed relays switch much faster than armature relays, have very low contact resistance, and offer the added benefit of being hermetically sealed. They do not have the capacity to carry voltages and currents as high as those of armature relays.

Mercury-wetted relays have good longevity, don't suffer from contact bounce, and have very low contact resistance. However, they are position sensitive, and must be mounted in the correct orientation to operate properly. Further, environmental concerns about mercury have limited their popularity.

Armature relays, found in the Agilent N2260A 40-channel multiplexer module, are the most commonly used type because of their ruggedness and ability to handle higher currents and voltages. Armature relays usually have low resistance, but generally have slower switch times and are somewhat more susceptible to arcing than other relay types. Some armature relays are sealed; others are not.

Solid-state relays are typically used for switching high-power circuits such as AC line voltages. They have no moving parts and are arc-free. However, they generally have a higher "on resistance" than is acceptable in low-level signal switching applications.

Table 1 summarizes the characteristics of typical instrumentation switches.

TABLE 1. Switch Performance Comparison (typical)

Type	Switch Speed	Thermal Offset	3dB BW	Current Rating	Max Input
General Purpose	7-16 ms	3-7 μ V	10 MHz	1-5 A	125-300 V
FET	0.16 ms	25 μ V	500 kHz	1 mA	16 V
Matrix	7 ms	3-7 μ V	10 MHz	1-2 A	200-300 V
RF Mux	7 ms	6 μ V	0.3 - 3 GHz	0.5-1 A	24-42 V
Microwave	30 ms	NA	18-20 GHz	NA	NA

Predicting Relay Life Spans

Relay manufacturers specify how long their relays will last, but the expected lifetime will vary depending on the loads they are subjected to. For resistive loads, manufacturers' specifications are fairly accurate. But if capacitive or inductive loads are used, a relay's life span will be shorter than the manufacturer's specification; how much shorter depends on the type of loads being switched. Derating provides a realistic picture of how long a relay will last.

Loads used in signal switching can be classified into five general groups: resistive, inductive, capacitive, motor, and incandescent. Resistive loads are assumed when manufacturers rate their relays. The load is a purely resistive element, and it is assumed that the current flow through the contacts will be fairly constant. In the real world, even simple resistive loads have inductance, and some increase in current may occur due to arcing during "make" or "break". Under ideal conditions, a relay with a purely resistive load can be operated at its stated voltage and current ratings and attain its specified lifetime. However, industry practice is to derate the relay's stated lifetime to 75 percent.

Switching inductive loads is difficult, primarily because current tends to continue to flow in inductors even as contacts are being broken. The stored energy in inductors induces arcing, so arc-suppression schemes are frequently used. For switching inductive loads, relay lifetime should be derated to 40 percent of the resistive load rating.

Capacitors resemble short circuits when they are charging, so the inrush current from a capacitive load can be very high. Series resistors are often used to limit inrush current; without a limiting resistor, contact welding may occur. For switching capacitive loads, relay lifetime should be derated to 75 percent of the resistive load rating.

Motor loads have special requirements: When an electric motor starts up, it has very low impedance and requires a large inrush current to begin building a magnetic field and begin rotating. Once it is running, it generates a back electromotive force (emf), which can cause a large inductive spike when the

switch is opened. The result is a large inrush current at "turn-on" and arcing at "turn-off". For switching a motor load, industry practice is to derate relay lifetime to 20 percent of the resistive load rating.

An incandescent lamp is considered a resistive load. However, the resistance of a hot tungsten filament is 10 to 15 times greater than its resistance when it is cold. The high inrush current into a cold filament can easily damage relay contacts. For switching incandescent loads, relay lifetime should be derated to 10 percent of the resistive load rating.

Prolonging Relay Life

The switching subsystem of a test system typically accumulates a large number of switch closures over time, so prolonging relay life is important. With the exception of solid-state relays, the most common relay types rely on the mechanical closing of metal-based contacts that are covered with a thin surface film. As these electrical contacts are closing, a large electrical field is generated between them, which can initiate an arc. An arc also can form when these contacts open. This is particularly true if the load being switched is inductive. Arcing, and the associated welding of contacts, affects relay contact reliability and life span. Other factors that affect contact reliability and life span include the types of loads being switched, high-power or high-voltage switching, the heat capacity and thermal resistance of the contacts themselves, and the surrounding ambient temperature.

Naturally, to achieve the expected relay life span, the voltage, current, and power levels of the signals being switched must be less than the maximum specified for the relay contacts. Switch contacts often can carry more energy than they can break at a switching point. In all cases, the relay contacts will last longer when switching lower energy.

Relay cycle counters are often integrated into a switch subsystem to count the number of cycles for each relay. This allows replacement of the relay before it fails. As described above, the life of a relay, or the number of actual operations before failure, depends on

the applied load, switching frequency, and environment. For example, the life span of the relays in the modules for the Agilent 34970A data acquisition/switch unit have a relay lifetime from 10,000,000 to 100,000,000 operations with typical signal levels. For the Agilent 34901A, 34902A, 34903A, and 34904A modules, the switch life with no load is 100M (typical) and the switch life at the rated load is 100k (typical).

Surge-Suppression Circuits

Surge-suppression circuits may be used to limit the surge current into the relay contacts. Whenever a relay contact opens or closes, electrical breakdown or arcing can occur between the contacts. Arcing can cause high-frequency noise radiation, voltage and current surges, and physical damage to the relay contacts. For capacitive loads, a simple resistor, inductor, or thermistor can be used in series with the load to reduce the inrush current. For inductive loads, techniques to clamp the voltage will help to reduce the inrush current. Clamps, a diode, a zener diode, a varistor, or a resistor/capacitor (RC) network can be placed in parallel with the load as a snubber or suppression circuit.

RC Protection Networks

For RC protection networks, the protection resistor (R_p) must be selected as a compromise between two resistance values. The maximum acceptable relay contact current (I_{max}) determines the minimum value of R_p . For a maximum allowable relay current (I_{max}) of 2 amperes DC or AC rms, the minimum value for R_p is V/I_{max} , where V is the peak value of the supply voltage.

$$R_p = \frac{V}{I_{max}} = \frac{V}{2}$$

Usually, the maximum value for R_p is made equal to the load resistance (R_L). Therefore, the limits on R_p can be stated as:

$$\frac{V}{I_{max}} < R_p < R_L$$

The actual value of the current (I_o) in a circuit is determined by the equation:

$$I_o = \frac{V}{R_L}$$

V is the peak value of the source voltage and R_L is the resistance of the load. The value for I_o is used to determine the value of the protection network capacitor (C_p).

Several factors must be considered to determine the value of the protection network capacitor (C_p). First, the total circuit capacitance (C_{tot}) must be such that the peak voltage across the open relay contacts does not exceed the maximum voltage rating of the relay. For a rating of 300 Vrms, the equation for determining the minimum allowable circuit capacitance is:

$$C_{tot} > (I_o / 300)^2 \times L$$

L is the inductance of the load and I_o is the current value calculated earlier.

The total circuit capacitance (C_{tot}) is made up of the wiring capacitance plus the value of the protection network capacitor C_p . Therefore, the minimum value for C_p should be the value obtained for the total circuit capacitance (C_{tot}). The actual value used for C_p should be substantially greater than the value calculated for C_{tot} .

Using Varistors

A varistor can be used when adding an absolute voltage limit across the relay contacts. Varistors are available for a wide range of voltage and clamp energy ratings. Once the circuit reaches the varistor's voltage rating, the varistor's resistance declines rapidly. A varistor can supplement an RC network, and is especially useful when the required capacitance (C_p) is too large. **Figure 11** shows an RC protection network circuit with a varistor.

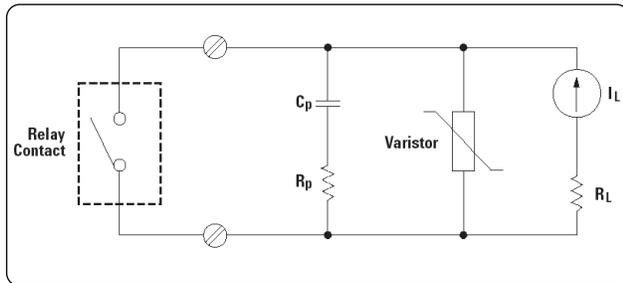


Figure 11. *Suppression circuit for limiting surge voltage*

Summary

Careful design of the switch subsystem of a test system is critical to testing success, as nearly all of the important test signals will flow through it. Concentration on noise reduction and signal integrity will allow for quality measurements, while choosing the proper switch topology will impact the cost, speed, safety, and overall functionality of the test system.

The topology of the switch subsystem is important for ensuring that all connections that need to be made can be made in an appropriate manner. It may be necessary to optimize the switch subsystem for high-speed measurements, low noise, or high-frequency signals. Selection of the relays used to implement the switch topology is very important, as it affects the type of circuits and systems that can be tested, as well as test-system reliability and accuracy. The topology selected must be able to achieve the level of automation required.

A switch subsystem should not be designed at the last minute and thrown together. A switch subsystem that is not carefully designed or used as intended can produce invalid test results, delaying product development or allowing a product to be shipped that does not meet its design requirements.



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