Test System Signal Switching

Application Note

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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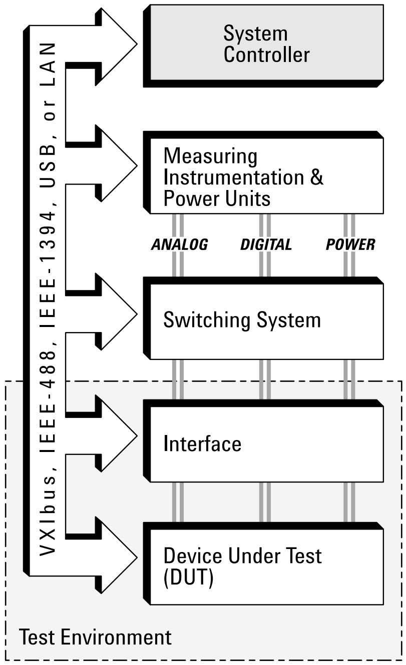

Figure 1. ***A generic test-system architecture. Nearly all analog, digital, and power signals pass through the switch subsystem.***

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 34980A switch/measure subsystem holds 8 of the available modules. Modules that provide simple relay multiplexing can be combined with modules that switch RF or provide digital or analog stimulous.

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.

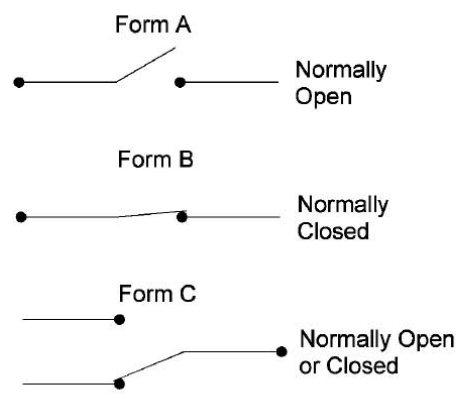

Figure 2. ***Simple relay configurations***

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.

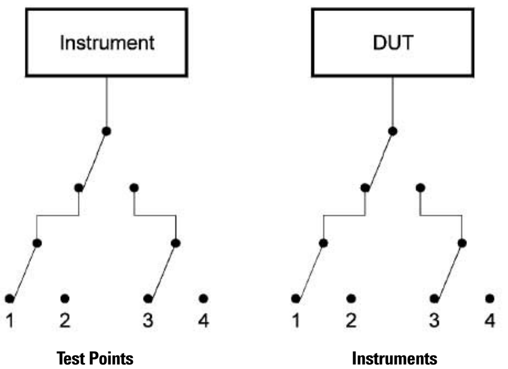

Figure 3. ***A binary switching ladder using form C relays***

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 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.

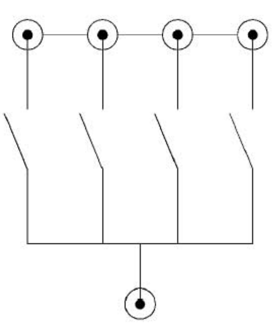

Figure 4. ***A single-ended multiplexing topology used at higher frequencies. Only the signal conductor is switched; the shield is common to all signals.***

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.

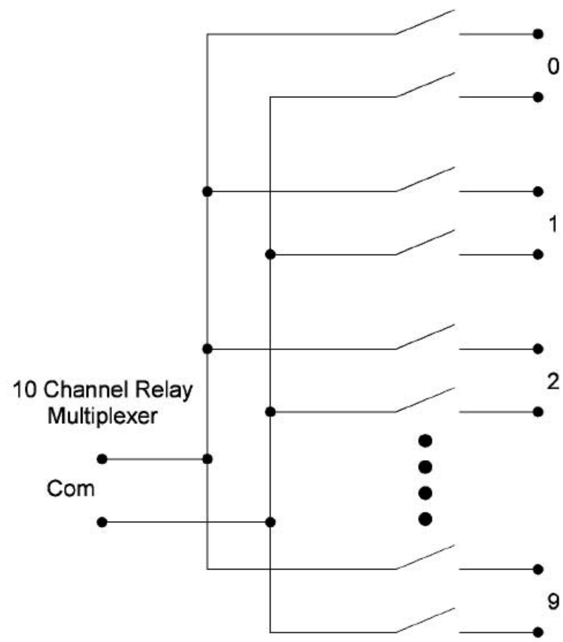

Figure 5. ***A two-wire multiplexing topology. This 10-channel relay multiplexer can be used for floating measurements because both conductors, the signal and the ground return, are connected to the common bus at the same time.***

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.

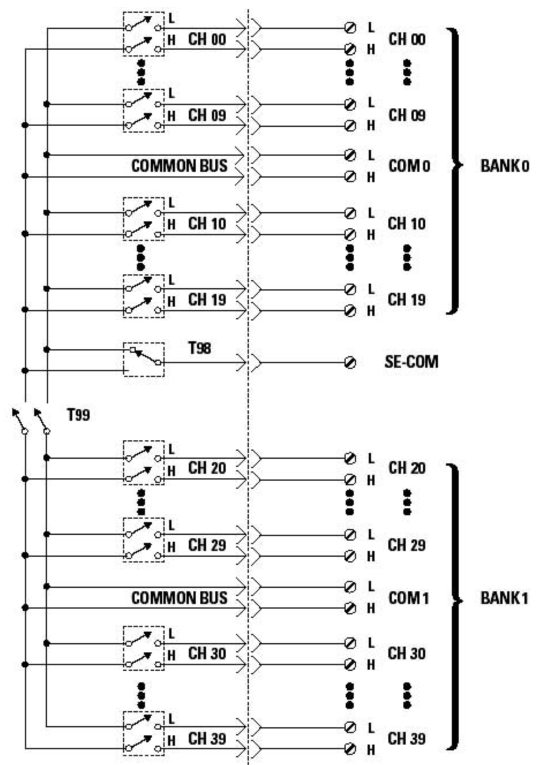

Figure 6. ***The Agilent N2260A can be configured as an 80-channel 1-wire, 40-channel 2-wire, or 20-channel 4-wire multiplexer.***

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.

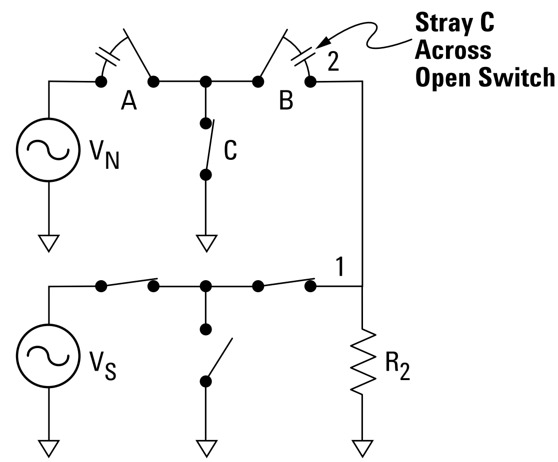

Figure 7. ***A simplified circuit diagram illustrating T-switching. Conductor 2 is open, so its "C" switch is closed, providing a low-impedance path to ground.***

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 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.

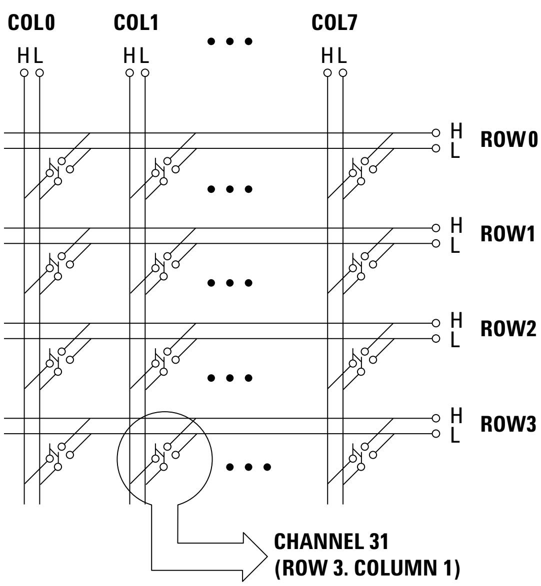

Figure 8. ***A full crossbar matrix, which allows two-wire connection from any point to any point***

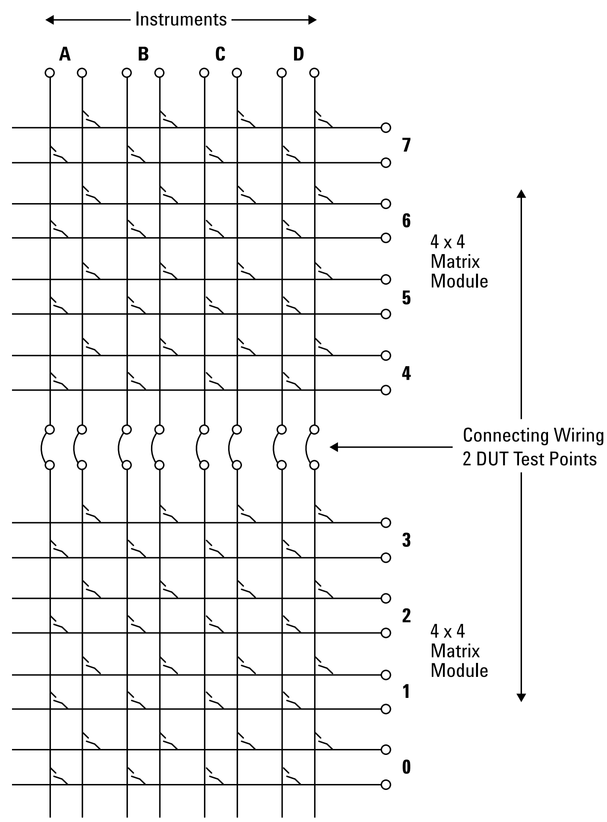

Figure 9. ***An example of connecting multiple matrix cards together to increase the size of the switching system***

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 10a 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.

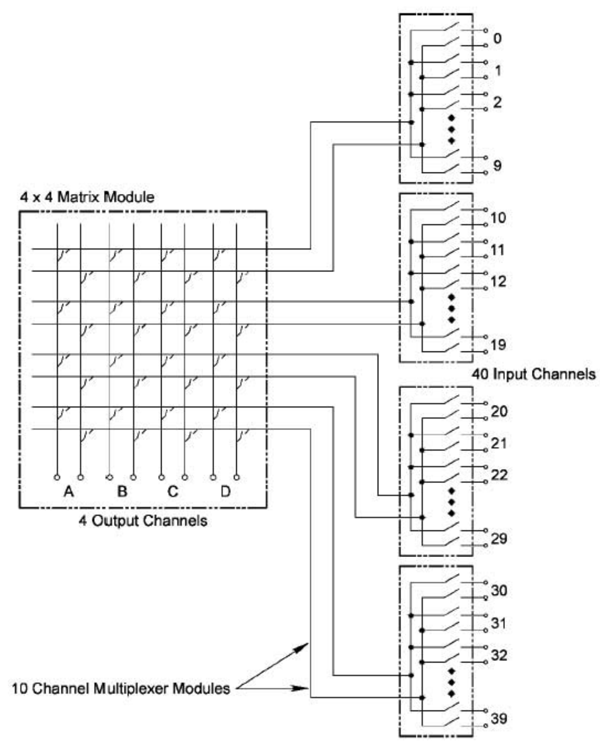

Figure 10a. ***Multiplexers can be used to effectively and economically expand the number of inputs or outputs of a matrix, although this switching topology does not have the unlimited flexibility of a full crossbar matrix.***

Internal Matrix

The Agilent 34980A with its four 2-wire internal analog buses and optional internal DMM makes this kind of external wiring unnecessary. Multiple multiplexers can connect to the built-in analog buses. You can route your measurements directly to the internal DMM, or you can connect to external instruments through the analog bus in the mainframe. And since there are four 2-wire buses available for each of eight modules, you can dedicate one bus for use with the internal DMM and use the other three buses for module extensions or additional signal routing between modules, reducing your wiring needs.

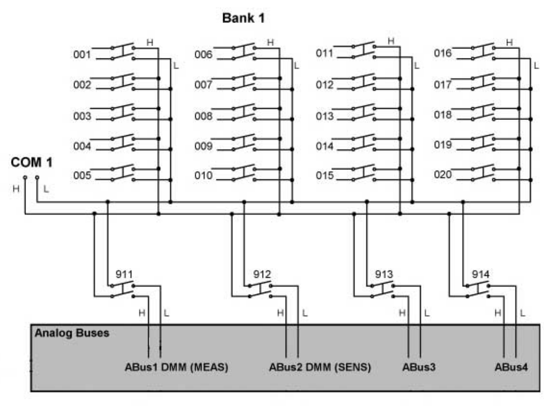

Figure 10b. ***The Agilent 34980A provides internal busses to expand multiplexer modules without the need for additional Matrix cards. Up to 8 multiplexer cards can be connected to the analog busses.***

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 electromechanical 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.

Three types of relays are commonly used in switching and signal routing: reed relays, armature relays, and FET switches. Each offers distinct advantages and disadvantages, and each works best for certain applications.

Reed relays, used in the Agilent 34923A 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.

Armature relays, found in the Agilent 34921A 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.

FET switches, found in the Agilent 34925A, have no moving parts and are arc-free. However, they generally have a higher "on resistance." Switching speeds are the highest of all switches.

Table 1 summarizes the characteristics of typical instrumentation switches.

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.

TABLE 1. Switch performance comparison (typical)

Type	Switch speed	Thermal offset	3dB BW	Current Rating	Max Input
Armature	7-16 ms	3-7 μV	10-50 MHz	1-5 A	125-300 V
FET	~1 ms	3-25 μV	1 MHz	1 mA-50 mA	16 V
Reed	2 ms	1-50 uV	30 MHz	0-0.5 A	125-300 V
RF Mux	7 ms	NA	0.3 - 3 GHz	0.5-1 A	24-42 V
Microwave	30 ms	NA	18-20 GHz	NA	NA

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 electromagnetic 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.

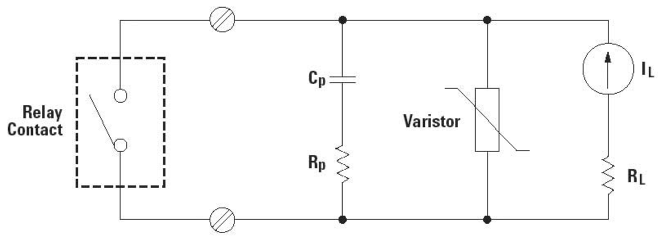

Figure 11. ***Suppression circuit for limiting surge voltage***

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.

Maintaining Signal Integrity

Sources of electronic noise

The measurement of low level signals in a test system environment can best be accomplished with careful attention to the details of grounding and shielding. The following are major offenders of noise coupling into these systems:

1. Conductively coupled noise
2. Coupling through a common impedance
3. Electric and magnetic fields

Besides these sources of noise, some systems are sensitive to noise from galvanic action, thermocouple noise, electrolytic action, triboelectric effect, and conductor motion. In electronic test systems designed for the testing of electronic modules, the important noise sources are generally the following:

Conductively coupled noise

The easiest way to couple noise into the circuit is on the conductor leading into the circuit. A wire running through a noisy environment has an excellent chance of picking up unwanted noise and transferring it to the circuit. Major offenders are often the power supply leads connected to the circuit.

Coupling through a common impedance

Common impedance coupling occurs when currents from two different circuits flow through a common impedance. The ground voltage of each is affected by the other. As far as each circuit is concerned, the ground potential is modulated by the ground current flowing from the other circuit in the common ground impedance.

Noise Coupling

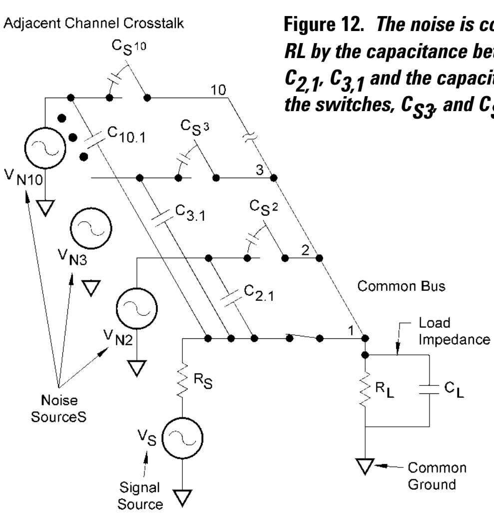

Figure 12. ***The noise is coupled onto RL by the capacitance between leads $C_{2,1}$, $C_{3,1}$ and the capacitance across the switches, C_{S3}, and C_{S2}.***

Electric and magnetic fields

Radiated magnetic and electric fields occur whenever an electric charge is moved or a potential difference exists. In a circuit, high frequency interference may be rectified and appear as a DC error. Particularly, radio and TV broadcasts in close proximity to the circuit of interest will tend to cause this kind of problem. Extremely strong fields can cause non-linear behavior of active circuitry without being suspected. Hence, it is imperative to shield sensitive circuitry from these fields.

Sources of noise in an automatic system

Of particular importance to the test engineer is knowing the source of the unwanted noise in his system. A simple list of rules may be helpful in reducing unwanted noise, but it is seldom enough for an understanding of where the noise is coming from.

In many cases the noise culprit is the adjacent channel in the system. A look at the simplified equivalent circuit in **Figure 12** shows that most of the capacitance in the switch system resides across the switch contacts and between the adjacent conductive paths. Since noise coupling is a function of area and proximity, a simple way to reduce the coupling is to separate the switches and the conductors from each other. This is not practical in many cases. Increasing the switch density is a desirable objective; it gives you more capability in a smaller package. Further, the systems being tested today tend to be much more complex and have larger point counts than ever before. Hence, you are faced with a dilemma of having to increase component density and the distance between channels at the same time.

One solution to this problem is to connect the large amplitude signals as far away as possible from the low-level signal leads. In addition, ground leads should be placed between the signal leads to provide a convenient path for the interfering noise.

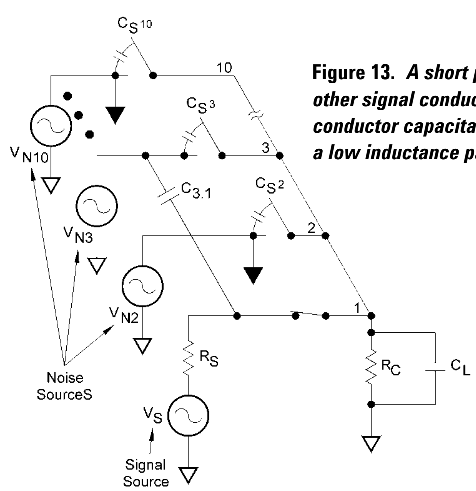

Figure 13. ***A short placed on every other signal conductor reduces the conductor capacitance and provides a low inductance path to ground.***

Noise Reduction

Noise reduction techniques apply equally to single point systems and multi-point systems. Let's look at the following topics:

1. Shielding
2. Grounding
3. Balancing
4. Isolation

Shielding

Shielding against capacitive coupling
Shielding against noise in systems involves shielding against both capacitive (electric) and inductive (magnetic) coupling in the system. Capacitive noise coupling between channels is both the easiest to understand and shield against in a test system.
As **Figure 14** shows, the coupling of noise from one conductor to the other is a result of the capacitance between the conductors. For a load resistance R, much less than the impedance (because of lower frequency) formed by the parallel combination of the capacitance to ground of the signal conductor and the capacitance between the conductors, the noise voltage is:

$$V_N = j\omega RC_{12}V_1$$

C_{1G} does not couple noise into the signal conductor #2. Implied here that:

$$R < 1/[j\omega(C_{12} + C_{2G})]$$

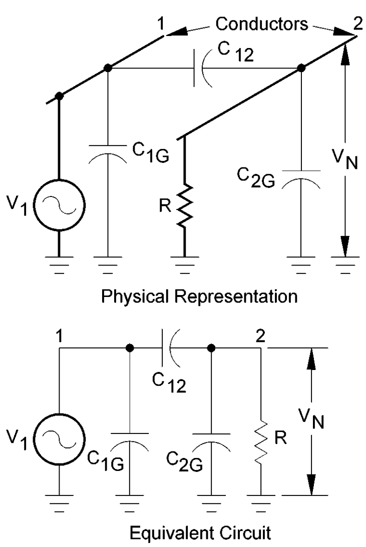

Figure 14†. ***Capacitive coupling between two conductors.***

If you could reduce the capacitance, C_{12}, then the noise voltage coupled into the conductor would be reduced. Physical separation will accomplish up to about 8 dB of noise reduction for a distance of 40 times the diameter of the conductor. More separation between the conductors has little effect. Another alternative is to operate at a lower resistance. Loading or mismatching may make this unfeasible.

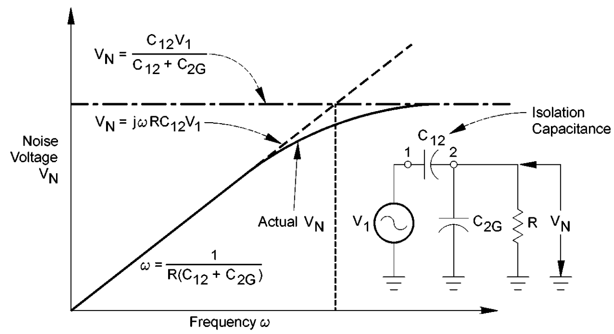

Figure 15†. ***Frequency response of capacitive coupled noise voltage.***

Surrounding the signal conductor with a grounded shield with a uniform electric field (the geometry of the shield is smooth) reduces the noise voltage on the signal conductor to zero provided the conductor does not extend beyond the shield at high frequency. If the shield is not grounded, then the noise voltage picked up by the center conductor is equal to the noise voltage on conductor 1. The shield merely couples the noise voltage as shown in **Figure 16.**

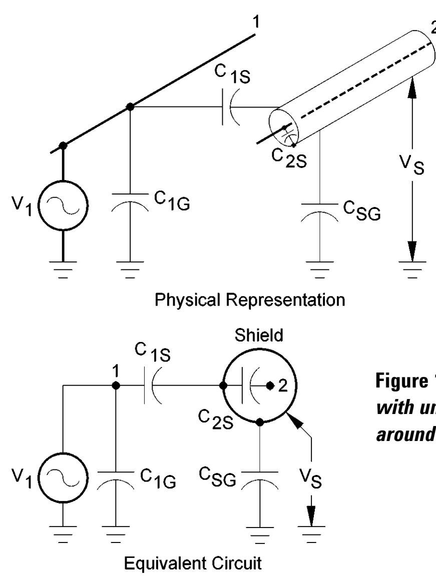

Figure 16†. ***Capacitive coupling with unguarded shield placed around receiver conductor.***

† Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

If the center conductor is exposed beyond the confines of the shield. and it has a finite resistance to ground, then the circuit is as shown in **Figure 17.** Again the noise voltage reduces to:

$$V_{N'} = j\omega RC_{12}V_1$$

Now however, C_{12} is greatly reduced because of the shield. If the shield is braided or not uniform then the effect of the holes in the shield must be included in C_{12}.

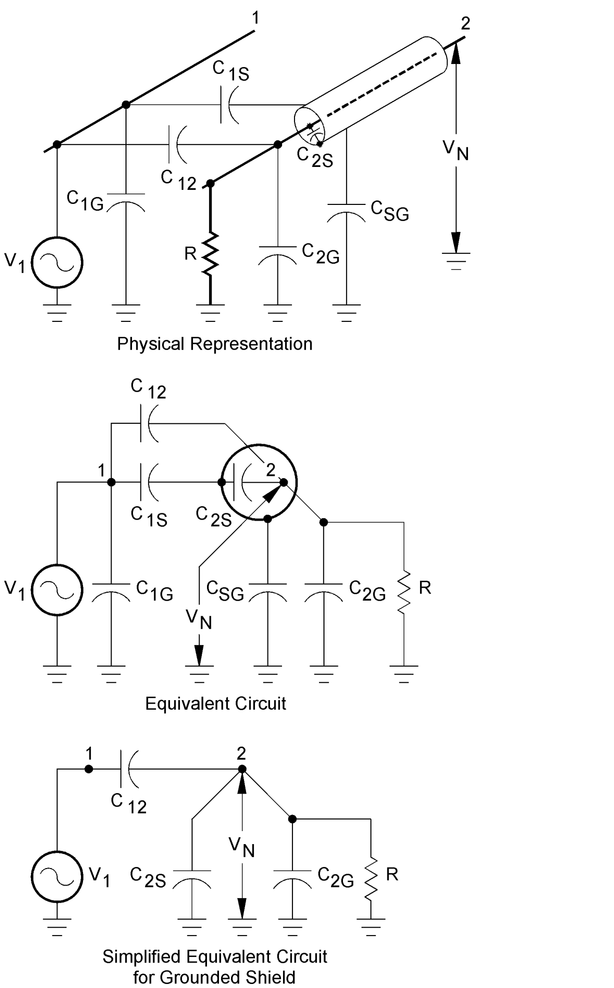

Figure 17†.
Capacitive coupling when receiving conductor has resistance to ground.

Inductive coupling is much more difficult to eliminate than capacitive coupling. In fact, the above illustration for excellent electric field shielding has no effect on inductively coupled noise.

An important derivation for inductive coupling is that the mutual inductance between shield and the center conductor equals the shield inductance.

$$M = L_S$$

In this case, the two conductors, the shield and the center conductor, do not even have to be coaxial.

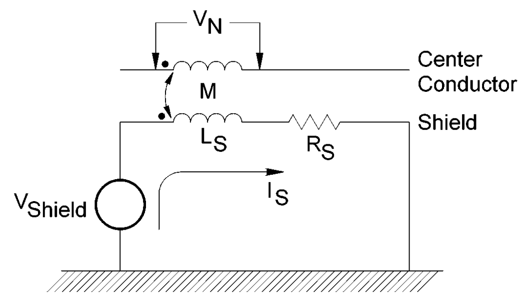

Figure 18†. ***Equivalent circuit of shielded conductor.***

From the circuit diagram in **Figure 18** and the fact that $L_S = M$.

We can derive the following relationship:

$$V_N = \frac{j\omega V_{shield}}{j\omega + R_s/L_s}$$

The 3-dB point on the graph of V_N versus frequency is defined as the cutoff frequency of the shield, ω_c. It can be shown that this frequency is $\omega_c = R_s/L_s$

† Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

Shielding against inductive radiation
If current is allowed to flow in the shield by connecting both ends of the shield to ground, at 5 times above the cutoff frequency, w_C, most of the noise current flows in the shield and cancels the noise current flowing in the center conductor. Below this frequency the ground plane carries most of the noise current and the shield is not effective in containing the noise. Hence, for audio and higher frequency applications the shield should be grounded at both ends. The noise reduction is a result of the field generated by the current in the shield that cancels the conductor's field and has little to do with the magnetic properties of the shield material.

Shielding against magnetic reception
Since inductive noise coupling is proportional to the loop area cutting the magnetic flux of the noise, receiver circuits can be best protected against magnetic fields by decreasing the area of the receiver loop.

Referring to **Figure 19C**, a shield placed around the conductor does not change the loop area and therefore provides no magnetic shielding. In **Figure 19B**, above the cutoff frequency, w_C, the circuit provides excellent magnetic field protection; however, below cutoff frequency most of the current will return through the ground plane and not through the shield. Since the shield is one of the conductors, any noise current in it will produce an IR drop in the shield and appear in the circuit as a noise voltage. If there is a difference in ground potential between the two points in the ground plane, this too will produce noise voltage in the circuit. Whenever a shield is used in a circuit and is grounded at both ends of the circuit, only limited low frequency magnetic field protection is possible because of large noise currents induced in the ground loop.

For maximum protection against induced noise at low frequencies, the shield should not be one of the signal conductors and one end of the circuit must be isolated from ground.

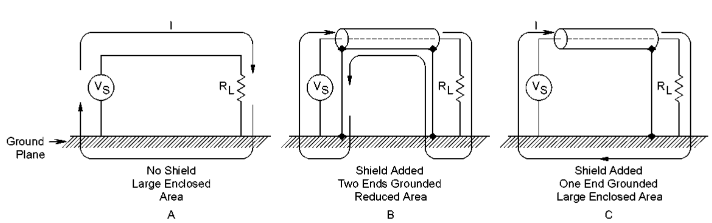

Figure 19†. ***Effect of shield on receiver loop area.***

Coaxial cable versus twisted pairs

Twisted pairs, where the wires are twisted together to reduce the loop area, and shielded twisted pairs should be used for applications up to a few hundred kHz. Above this frequency these cables are prone to signal loss. By contrast, the impedance of coax cable is relatively uniform from DC to VHF (30 MHz to 300 MHz) frequencies.

A coaxial cable with its shield grounded at one point provides a substantial amount of protection from capacitive pickup. A double shielded or triaxial cable with insulation between the two shields provides the maximum protection against noise coupling. Since the noise current flows through the outer shield and the signal return current flows through the inner shield, the two currents do not flow through a common impedance for noise coupling. Fortunately (since triaxial cables are expensive and awkward to use), above 1 MHz skin effect on the shield of coaxial cable tends to simulate triaxial cable. The noise current will flow on the exterior of the shield and the signal return current will flow on the interior of the shield.

Up to a few hundred kilohertz the shielded twisted pair cable has performance comparable to triaxial cable without the expense and awkwardness.
An unshielded twisted pair, unless it is used in a balanced circuit, offers little protection against capacitive pick-up but has good noise immunity from magnetic pickup.

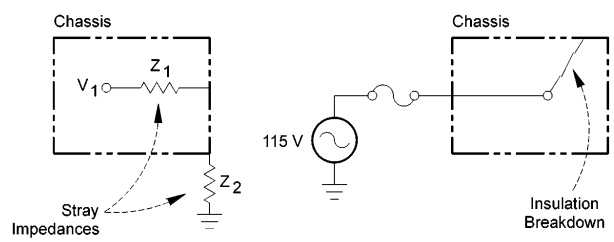

Figure 20†. ***Instrument chassis should be grounded for safety. Otherwise, it may reach a dangerous voltage level through stray impedances (left) or insulation breakdown (right).***

† Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

There are two definitions of ground:

1. A signal ground is an equipotential circuit reference point for a circuit or a system.
2. A signal ground is a low impedance path for current to return to the source.

The first definition is the classical interpretation of the idealized ground. The second emphasizes the realities of the IR drops that can occur in the ground plane and couple noise into the signal conductor.

The design objectives of a grounding system are:

1. To minimize the noise voltage generated by currents from two or more circuits flowing through a common ground impedance.
2. To avoid creating ground loops that are susceptible to magnetic fields and differences in ground potential.

Improper grounding can be a primary noise source

Grounds can be divided into two parts; safety and signal grounds. Safety grounds are provided so that a breakdown in impedance between the equipment chassis and the high voltage line of the power line will result in a low impedance path to ground. See **Figures 20 and 21**.

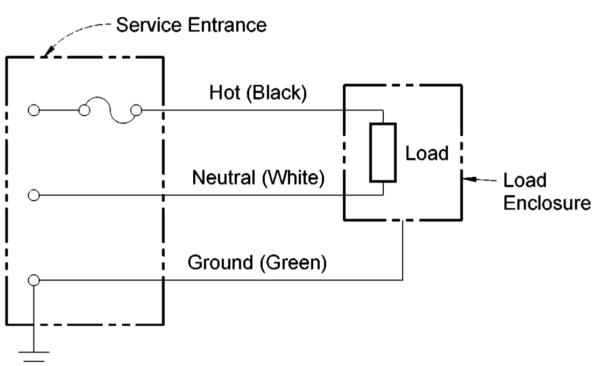

Figure 21[†]**.** ***Standard 115 V AC power distribution circuit has three leads.***

Single point ground systems

Signal grounds are either single point or multi-point grounds. Single point grounds can be connected in series or parallel in systems. For noise coupling the least desirable grounding scheme is the series ground, but it is also the least expensive and the easiest to wire. It is therefore the most widely used. For non-critical applications the series ground may work satisfactorily. The most critical circuits should be placed nearest to primary ground point. See **Figure 22.**

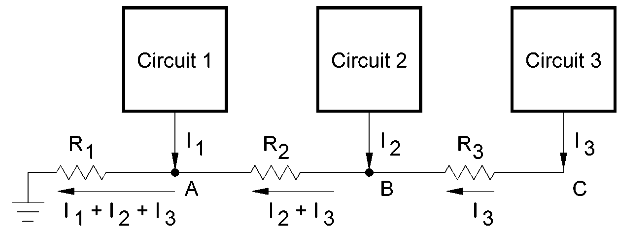

Figure 22[†]**.** ***Common ground system is a series ground connection and is undesirable from a noise standpoint but has the advantage of simple wiring.***

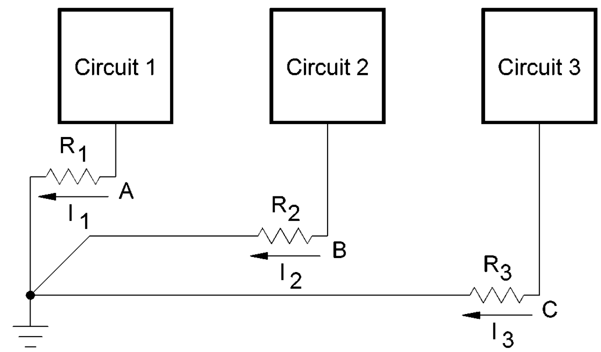

Figure 23[†]**.** ***Separate ground system is a parallel ground connection and provides good low-frequency grounding, but is mechanically cumbersome.***

The parallel ground shown in **Figure 23** is the most desirable configuration for frequencies in the audio range. This configuration eliminates cross coupling between ground currents through different circuits. The scheme, which is not as simple as the series connections, is awkward to wire and use.

At high frequencies the parallel single point connection is very limited. It is here that the inductance of the ground conductors increases the ground impedance and also produces capacitive coupling between the ground leads. This situation worsens as the frequency increases to the extent that the ground leads begin to act like antennas and radiate noise. As a rule, ground leads should always be less than 1/20th of a wavelength to prevent radiation and maintain low impedance.

[†] Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

Multipoint ground systems

For high frequency applications the multi-point grounding system should be used. Typically, the circuits are connected to the nearest available low impedance ground plane, normally the system chassis. However, just as parallel single point configurations are not effective for high frequencies, multi-point ground systems should be avoided at low frequencies. In multi-point ground systems all the ground currents from all the circuits flow through a common ground impedance, the ground plane, as shown in **Figure 24.**

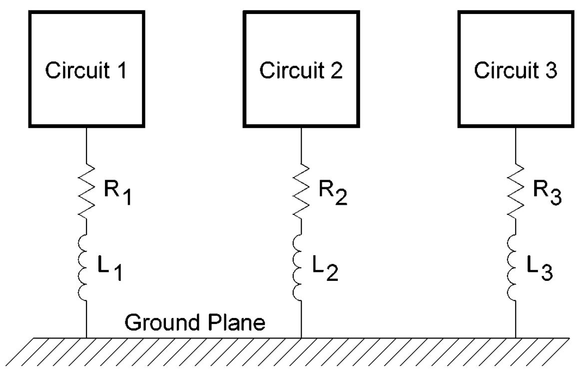

Figure 24†. ***Multi-point ground system is a good choice at frequencies above 10 MHz. Impedances R, - R3, and L1 - L3 should be minimized.***

Grounding summary

Normally, at frequencies below 1 MHz a single point ground system is preferred; above 10 MHz the multi-point ground is best. From 1 to 10 MHz, a single point ground system can be used as long as the length of the longest ground return is less than 1/20th of a wavelength. If this is not possible, then a multi-point should be used.

For practical reasons, most systems require three separate ground returns. Signal grounds should be separate from hardware grounds and noisy grounds like relay and motor grounds. In sensitive systems, for example, separating the signal grounds into low level and digital grounds prevents the higher level, much noisier digital signals, from coupling into the low level leads. If AC power is distributed throughout the system, the power ground should be connected to the chassis or hardware ground, as shown in **Figure 25.**

A single ground reference system should always be used for low level work. If it is not used, any differences in ground potential will show up as noise on the signal path. A measurement system with a return path through two grounds will produce a noise voltage across the measurement terminals of the instrument.

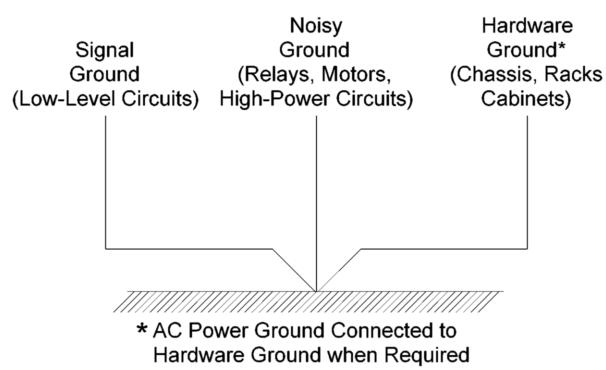

Figure 25†. ***These three classes of grounding connections should be kept separate to reduce noise coupling.***

† Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

Grounding shield cable and connectors

Shields on cables used at frequencies less than 1 MHz should only be connected to a ground at one point. In the case of shielded twisted pair, to connect ground at more than one point may inductively couple unequal voltages into the signal cable and be a source of noise. The IR drop in the shield of a coaxial cable will couple into the signal conductor, and is a problem if the shield is connected to ground at more than one point.

Since we must connect ground somewhere, where should that be?

1. For a grounded amplifier and an ungrounded source, the shield should always be connected to the amplifier common terminal even if this point is not earth ground.
2. For an ungrounded amplifier and grounded source, the shield should be connected to the source common terminal, even if it is not at earth ground.

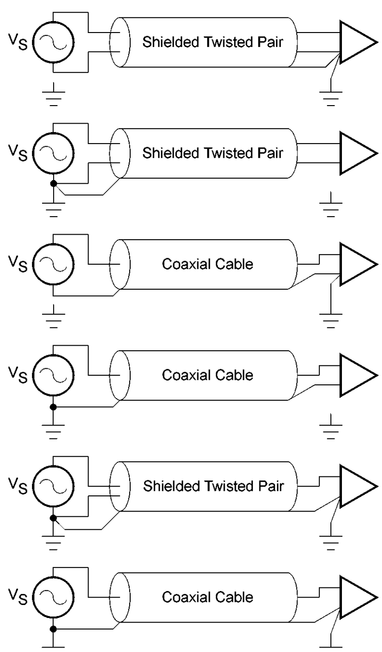

Figure 27[†]. ***Preferred grounded schemes for shielded twisted pairs and coaxial cable at low frequency. The grounds may have large potential differences that can cause ground loops and couple noise into the circuits.***

3. If both source and amplifier are grounded, we have no choice but to ground the shield at both ends. This is the least desirable of all circuit configurations for noise reduction. **Figure 27** shows the proper connections for shielded twisted pair and coaxial cables at low frequency.

Other methods of reducing ground coupled noise

Ground loops in very noisy environments can be broken by the use of isolation transformers as shown in **Figure 28.** In cases where a DC path must be maintained a longitudinal choke can be used to suppress higher frequency loops. Optical isolation likewise can be used to break ground loops.

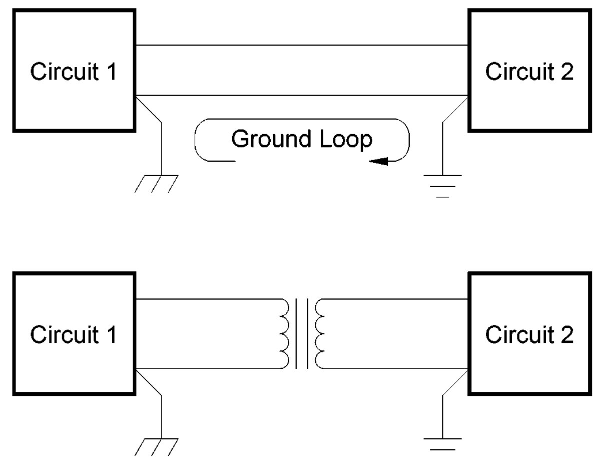

Figure 28[†]. ***A ground loop between two circuits can be broken by inserting an isolation transformer.***

Other methods of reducing the effects of ground loop noise apply directly to the measuring receiver amplifier. The receiver can be configured to minimize the effect of ground loops by using a balanced input. Even more noise rejection can be obtained at low frequency with a guard shield around the amplifier.

Up to this point we have discussed shielding only at low frequencies. Shield grounding at high frequencies, above 1 MHz, requires more than one connection to ground to guarantee that the shield remains at ground potential. Besides, capacitive coupling between the shield and ground plane tends to complete the circuit at high frequency and makes the shield isolation difficult to impossible.

At high frequency it is common practice to ground the shield at every 1/10th wavelength to assure good grounding.

If there is any question about the ground in a system, it is better to isolate the questionable ground and find some other way of making a good ground connection.

[†] Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

A hybrid ground formed by inserting small capacitors every 1/10th wavelength provides a single ground at DC and multiple grounds at high frequency. Further, its performance can be characterized reliably.

Noise coupling in switching systems

The interface between your DUT and switching system provides an excellent opportunity for inadvertently introducing noise to your system. Follow these simple rules for the cable harness:

1. High and low level leads should not share the same cable harness.
2. Shield integrity should not be broken through the system -for low frequencies, the shield must be insulated to avoid grounding at some other point in the system.

For connectors follow these guidelines:

1. High and low level leads should be separated on the connector.
2. Ground leads should be placed between the signal leads where possible.
4. Any unused connector pins should remain between the signal leads and be grounded.
5. Cable shields should each have their own connector pin through the connector.

The sources of noise in the switching system are those generated internally by the circuitry driving the switches, by thermal unbalance across the switches, by noise coupling from other conductors in the system, and by noise generated outside the system. Thermal unbalance can either be minimized by a mechanical design that assures that all the contacts in the relay are subject to the same temperature gradient across the leads or by using latching relays. In this case the major source of thermal generation, the coil energy, is removed so that the relays are always in thermal equilibrium.

Noise coupling from adjacent channels into the measurement channel(s) presents a great danger to signal integrity. Proper shielding and grounding techniques can remove many of these problems in hard-wired systems, but when the signal must be selectively switched into an oscilloscope, counter, or some other measuring instrument, the problem can become acute.

Noise reduction techniques in switching systems

Tree switching is often used to reduce the stray open switch capacitance seen in large systems as a result of connecting the unused relays in parallel in the system. This capacitance is reduced by introducing a relay in series with the input relays. For a 20-channel multiplexer this series switch effectively reduces the stray capacitance seen by the measuring circuit to 1/20th the value without the tree switch. The result is less crosstalk and faster measurement settling time for the system. This is shown in **Figure 29.**

T-switching is a method by which all of the unused channels are isolated from the measurement bus by a low inductance path to ground. This isolation can be accomplished on a single conductor by inserting two additional contacts in the signal path. **Figure 30** illustrates the concept of T-switching. The result is excellent channel-to-channel signal isolation at high frequency on the same multplexer. As shown in **Figure 31.**

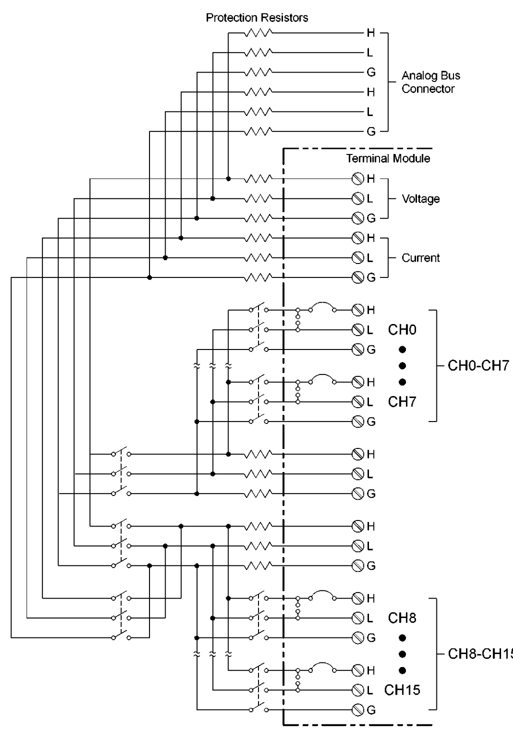

Figure 29. ***3-Wire multiplexing and tree switching are shown in this illustration of a 20 channel multiplexer card. By placing the tree switch in series with the input channels the effective capacitance of the unused cards in the system is reduced to 1/20th of the normal shunt capacitance in the system. This is very useful for large system configurations.***

† Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

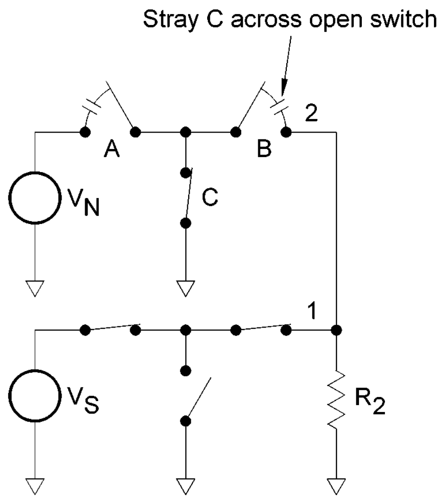

Figure 30. ***T-Switching.- this is a simplified circuit diagram of how T-switching works. Conductor 2 is open in this diagram; hence, its 'C' switch is closed prodding a low impedance path to ground.***

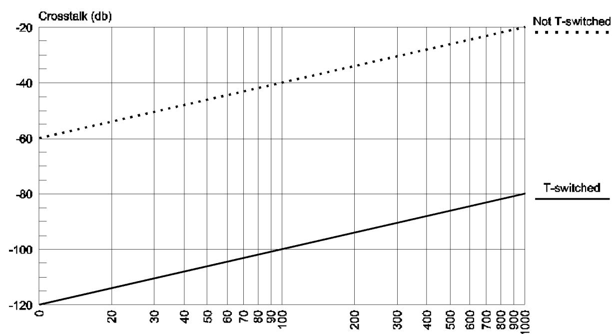

Figure 31. ***The effect of T-switching on Crosstalk. The effective capacitance between signal paths is minimized to the extent that up to 60 dB of crosstalk isolation is realized through T-switching.***

Impedance mismatching

Impedance mismatching in switching systems can cause many unpredictable measurements results, if the signal is either a high frequency cw waveform or is a digital signal with fast transition times. Basically, the reflected wave at the point of the impedance mismatch adds algebraically with the incident waveform creating a standing wave on the transmission line. The ratio of the sum of the peaks of these waves to the difference (the Voltage Standing Wave Ratio, VSWR) can be calculated from the differences in the characteristic impedance of the system and the switch.

For $Z_O > Z_L$ $\quad$ For $Z_L > Z_O$

$$VSWR = \left(\frac{Z_L}{Z_o}\right) \qquad VSWR = \left(\frac{Z_o}{Z_L}\right)$$

For lossless systems, Z_O is the characteristic impedance of the transmission line. Z_L is the load impedance.

As long as the wavelength of the input waveform is large compared to the cable length, these effects are minimal and can largely be ignored. For example, for coaxial airline, signals less than 10 MHz will generally cause no problems with reflections. To gain an understanding of this, simple calculation of the wavelength versus frequency can be made from the relationship:

$$\tau \times f = C$$

where:

τ = wavelength
f = frequency
C = speed of light in the media

For example:

Frequency	Wavelength
1 MHz	300 m
10 MHz	30 m
100 MHz	3 m

Many times high frequency cw signals are not common in systems, but there are many encounters with pulsed signals and pulsed signal routing. Fast transition time digital pulses will cause double triggering, double counting, and race conditions in the test system if there is a mismatch through the system.

Hence, it is important to know what signals are going to cause a problem and how to estimate the size of the problem.

The relative amplitude of the reflected waveform can be calculated from the VSWR specification for the switch from the relationships:

Where BW = Frequency

$BW \times t_r = .35$ and $E_r = E_i\left(\frac{V - 1}{V + 1}\right)$

t_r = pulse risetime

E_r = amplitude of the reflected wave.

E_i = amplitude of the incident wave.

V = the specified VSWR.

For example, let's look at the reflections of a 5 volt signal being routed through a switch with a VSWR of 2.0 at 100 MHz.

First, let's calculate the risetime of the signal from:

$$t_r = \frac{.35}{100x10^6} \quad t_r = 3.5 \text{ ns.},$$

We can calculate the amplitude of the reflected wave from

$$Er = 5\left(\frac{2 - 1}{2 + 1}\right) = 1.67V,$$

which for the sample case is equal to 33% of the amplitude of the incident waveform. In the case of a 5 volt signal, this amplitude could cause even TTL with risetimes of 3.5 ns to indicate a false state.

A Noise Reduction Check List†

When designing your system the following check list will be helpful in reducing noise.

A. Suppressing noise at source:

- ☐ Enclose noise sources in a shielded enclosure.
- ☐ Filter all leads leaving a noisy environment.
- ☐ Limit pulse risetimes.
- ☐ Relay coils should be provided with some form of surge damping.
- ☐ Twist noisy leads together.*
- ☐ Shield and twist noisy leads.
- ☐ Ground both ends of shields used to suppress radiated interference (shield does not need to be insulated).*

B. Eliminating noise coupling:

- ☐ Twist low level signal leads.*
- ☐ Place low level leads near chassis (especially if the circuit impedance is high).
- ☐ Twist and shield signal leads (coaxial cable may be used at high frequencies).
- ☐ Shielded cables used to protect low level signal leads should be grounded at one end only (coaxial cable may be used at high frequencies with shield grounded at both ends).*
- ☐ Insulate shield on signal leads.
- ☐ When low level signal leads and noisy leads are in the same connector, separate them and place the ground leads between them.*
- ☐ Carry shield on signal leads through connectors on a separate pin.
- ☐ Avoid common ground leads between high and low level equipment.*
- ☐ Keep hardware grounds separate from circuit grounds.
- ☐ Keep ground leads as short as possible.*
- ☐ Use conductive coatings in place of nonconductive coatings for protection of metallic surfaces.
- ☐ Separate noisy and quiet leads.*
- ☐ Ground circuits at one point only (except at high frequencies). *
- ☐ Avoid questionable or accidental grounds.
- ☐ For sensitive applications, operate source and load balanced to ground.
- ☐ Place sensitive equipment in shielded enclosures.
- ☐ Filter or de-couple any leads entering enclosures containing sensitive equipment.
- ☐ Keep the length of sensitive leads as short as possible.*
- ☐ Keep the length of leads extending beyond cable shields as short as possible.*
- ☐ Use low impedance power distribution lines.
- ☐ Avoid ground loops.*
- ☐ Consider using the following devices for breaking ground loops:
  - Isolation transformers
  - Neutralizing transformers
  - Optical couplers
  - Differential amplifiers
  - Guarded amplifiers
  - Balanced circuits

C. Reducing noise at receiver:

- ☐ Use only necessary bandwidth.
- ☐ Use frequency selective filters when applicable.
- ☐ Provide proper power supply decoupling.
- ☐ Bypass electrolytic capacitors with small high frequency capacitors.
- ☐ Separate signal, noisy, and hardware grounds.*
- ☐ Use shielded enclosures.
- ☐ With tubular capacitors, connect outside foil end to ground.*

*Low cost noise reduction.

A Systematic Approach to System Configuration

A systematic approach to configuring your system lets you organize the connections, the switching scheme, and the instrumentation needed to test your DUT. The following is a check list for system configuration:

1. Know what you want to test. Be sure that you're not overtesting the DUT. Overtesting is time consuming and costly.
2. Know your instrumentation.
3. Know the commercially available remedies for your testing problems.
4. Keep the number of crossbar matrix configurations to a minimum. The flexibility offered by the matrix configuration must be weighed against its increased switch capacitance, signal conductor to signal conductor capacitance, insertion loss, impedance mismatching, and cost. Generally, a different approach to the testing philosophy is needed if many matrices seem to be needed in the system.
5. Isolate signals that could interfere with low level signals and keep them physically separate in the system.
6. Maintain the shield integrity throughout your interface design. Ground shields at either the source or the receiver but not at both for lower frequency signal integrity. Ground shields at both ends for high frequency signal integrity. If both high and low frequencies are used in the system, a single point ground is usually best.

The approach to construct the test system is to list all the inputs and outputs to the DUT, to evaluate the type of switch needed to maintain the signal integrity for each input and output, to evaluate the test instrumentation needed, and to devise the smallest switching system possible consistent with the switching needs of the test system.

If you can set up the test instrumentation on the bench without the system interface and switching network connected, so much the better. Even manually running the test through the switching system is an aid to debugging the hardware and software for the later automation of the system.

A sample system

Let's look at a sample system that could be used to functionally test a DUT with a signal of up to 50MHz (**Figure 30**). The DUT is powered by the power supply and stimulated by the function generator. The DUT signal outputs are dependent upon the input frequency of the function generator. The measurements of these outputs are accomplished with a DMM, the oscilloscope, and the counter.

Test points	The DUT pin out
1	dc ground
2	+ 5 volts DC
3	+ 12 volts DC
4	Clock input
5	30 mV sinusoid with 4 times the clock frequency
6	DC level proportional to clock frequency (1 V/MHz) for instrument control
7	Trigger signal
8	Signal ground
9	5 volt sinusoid with 10 times the clock frequency
10	Pulse burst output capability

Instruments
54641A 350MHz oscilloscope
E3620A dual power supply
53131A universal counter
33250A programmable function generator
34980A Internal 6½ digit DMM Slot 1, 34931A, 4x8 armature matrix switch Slot 2, 34941A, quad RF multiplexer
PC with GPIB interface for instrument control

† Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

The testing tasks

1. 1a: Measure and set the power supplies to within 0.1% of their nominal values

   1b: Connect power supplies and measure after each connection
2. Measure the clock frequency of the function generator with the counter
3. Measure the signal frequency on TP5 with the counter
4. Measure the DC signal on TP6 with the DMM
5. Use the trigger signals on TP7 to capture the pulse burst on TP10 with the oscilloscope
6. Measure the pulse width of TP7
7. Measure rise time of the pulses on TP10
8. Measure the frequency of TP9 with the counter

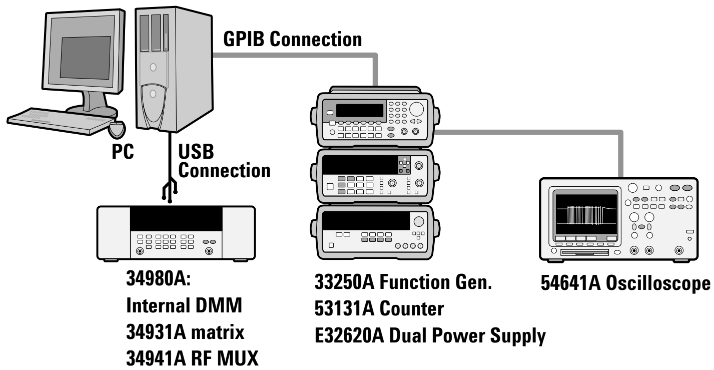

Figure 32. ***A typical small testing system consisting of the Agilent 34980A Multifunction Switch/Measure Unit with internal DMM, an oscilloscope, dual power supply, universal counter, and function generator.***

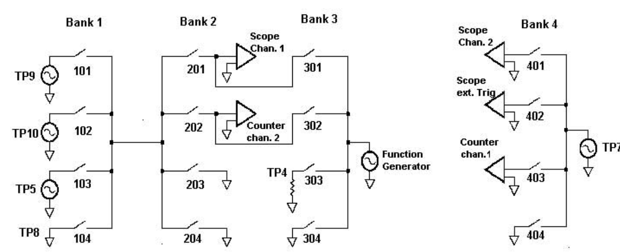

Figure 33a. ***The switching topology for the test system consists of 1 quad RF module and 1 matrix module. This represents the RF module used for the AC signals in slot 2.***

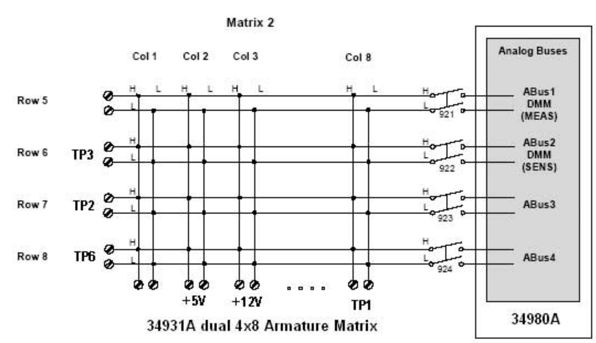

Figure 33b. ***The switching topology for the test system consists of 1 quad RF module and 1 matrix module. This represents the Matrix used for low frequency and DC switching. The DMM is internal to the 34980A and connected to row5 to make DC measurements in the Matrix module in slot 1.***

Task schedule

The sequence of switch closures necessary to accomplish the testing tasks is listed in Table 2.

Task #	Slot	Channel	Open/Close	Connection description
1a	1	921	Close	Internal DMM to row 5 matrix 2
	1	502	Close	DMM to +5V supply
	1	502	Open	
	1	503	Close	DMM to +12V supply
		503	Open	
1b	1	702	Close	+5 to TP2
	1	502	Close	DMM to +5V supply
	1	502	Open	
		603	Close	+12V to TP3
	1	503	Close	DMM to +12V supply
		503	Open	
		921	Open	
2	2	302	Close	Function Generator to Counter ch 2
		302	Open	
3	2	303	Close	Function Generator to TP4 clock input
		103	Close	TP5 to Bank 2 common of matrix
		202	Close	Common to Counter ch 2
		303	Open	
		103	Open	
		202	Open	
4	1	921	Close	Internal DMM to row 5 matrix 2
		501	Close	DMM to column 1
		801	Close	DMM column to TP6
		921	Open	
		501	Open	
		81	Open	
5	2	102	Close	TP10 Burst to matrix common
		201	Close	Common to scope ch 1
		402	Close	TP7 trigger to Scope ext trigger
		102	Open	
		201	Open	
		402	Open	
6	2	403	Close	TP7 pulse to counter
		403	Open	
7	2	102	Close	TP10 Pulse to common
		202	Close	Common to counter ch 2
		102	Open	
8	2	101	Close	TP9 signal to counter ch 2
		101	Open	
		202	Open	

Table 2. ***Task schedule for switch closure. This assumes that all channels are open at power up. 502 = close row 5 col 02***

Input and output considerations

Let's apply a systematic approach to the sample system by looking at our testing tools and the DUT. The test instrumentation presents a variety of input and output impedances. First, the oscilloscope has a choice of two impedances on each of its signal inputs, either 50Ω or 1 MΩ shunted by 16 pF. The oscilloscope trigger inputs are 1 MΩ shunted by 30 pF. The counter's input impedance is 1 MΩ shunted by 30 pF. Both the counter and the oscilloscope are single ended instruments. i.e., they have grounded amplifiers. The grounding scheme used with these instruments at high frequency is multipoint. The input impedance to the voltmeter is $10^{10}\Omega$ for DC measurements. The DMM is floating, i.e., it is an ungrounded amplifier. Its input is DC isolated from the chassis.

The output impedance of the function generator is 50Ω. To remain amplitude calibrated, the function generator must be terminated with 50Ω. The function generator is a grounded source. The output impedance of the power supply is a few milliohms. It is a floating source in which the output low is DC isolated from chassis.

Frequency considerations

To maintain the signal integrity of the function generator with 5 ns risetime, the frequency range of the switch has to accommodate a frequency of 70 MHz. This follows from the risetime-bandwidth relationship for Gaussian rolloff:

$$BW = \frac{.35}{T_r}$$

Hence, the frequency of the clock, even if constrained to be less than 10 MHz, requires at least a 70 MHz switch frequency range to avoid undue signal degradation. This leads directly to the consideration of VHF switching to perform this task.

Topology considerations

To measure the power supplies both under load and open circuit, the DMM has to interface to the circuit at the same time the power supplies are connected to the DUT. This forces us to use a matrix configuration. The ground connection to the power supply and DMM is referenced to the DUT to keep the ground at one point. If we were to connect the ground at the power supply to the DMM low, then we would create a ground loop that could cause noise coupling not only into the measurement circuits but also into the DUT.

Switch consideration

The RF cards in the switching system have a characteristic impedance of 50Ω for each group of 1 x 4 VHF multiplexers. The BW range of the VHF switches is 3 GHz for a single switch closure. The frequency range of the matrix switch is 30 MHz for a single switch closure.

Timing measurements and the DUT

The digital signals of the DUT have TTL compatible logic levels and the output impedance is a nominal 150Ω. The output impedance of the cw and low level DC outputs is 50Ω. The signal low of all output and input signals is referenced to the chassis low of the DUT.

The TTL compatibility of the digital input and output signals specifies the maximum fanout and the voltage levels necessary for operation of the DUT. If we used the 50 ohm oscilloscope input for transition time measurements, we could load the TTL output to the extent that the DUT circuit would stop functioning. We must select the high input impedance for oscilloscope measurements and compromise the transition time measurements. Fortunately, since we know the measurement effect of the input impedance on the transition time, it is easy to correct the measurement.

$$t_{unk} = \sqrt{t^2_{mea}, - t^2_{2.2Rch}\,C - t^2_{scope}}$$

where t_{unk} = the unknown risetime

t_{mea} = the measured risetime

t_{scope} = the oscilloscope's risetime

$t_{2.2Rch}C$ = the charging risetime of the parallel resistance of the generator and the oscilloscope and the oscilloscope's input capacitance.

Grounding

The high frequency circuits require multi-point grounding to reduce noise in the signal path. The low frequency signals require single point grounding to assure ground loop interruption. Also important to this application is the separation of the high frequency digital signals from the low level AC signal. This separation should extend to the switching and cabling used in the system.

Conclusion

In conclusion, there is a need to have two separate switching configurations to handle the test and power signals in this application. One is a coaxial VHF, common low, multiplexer configuration; the other is a floating, two conductor, matrix configuration. This allows the low level DC signals to be separated from the noisy digital signals. Further, ground loops can be avoided by interrupting them with the floating, two-conductor matrix.

Amplitude and risetime measurements are affected by the input and output impedances of the DUT and instruments. The amplitude calibration of the function generator and the signal loading of the TTL outputs are important. Care must be taken not to load the TTL outputs with the 50Ω input impedance of the oscilloscope. As a result, risetime measurements may require capacitance compensating circuitry or calculations for their correct determination

Summary

While the examples have not been exhaustive, they should give the systems engineer some insight into system switching. Signal integrity is only maintained through careful attention to the input and output characteristics of the DUT and the testing instrumentation, including the switch. Moderate frequencies and amplitudes are fairly easy to route and measure although care must be taken to avoid ground loops. Higher frequency or low level signals require special attention to the type of switch and the configuration of the switch to assure signal integrity in the system.

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