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Safety Guidelines for the Application, Installation, and Maintenance of Solid-State Control

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Foreword

This Rockwell Automation publication is formatted to harmonize with NEMA Standards Publication No. ICS 1.1-1987, also titled Safety Guidelines for the Application, Installation and Maintenance of Solid-State Control. The text of the NEMA Standard has been reprinted verbatim, with NEMA's permission, in the left column, captioned "NEMA Standard Text". The right column, captioned "Explanatory Information", contains Rockwell Automation comments and explanation. The comments provide supplementary information to the NEMA Standard to help the reader better understand the characteristics of industrial equipment employing solid-state technology. Rockwell Automation is solely responsible for the explanatory comments, which are not part of the NEMA Standard.

NEMA Standards Publication No. ICS 1.1-1984 (R1988, R1993, R1998, R2003) is available from the National Electrical Manufacturers Association, 2101 L Street, N.W., Washington, D.C. 20037.

Comments

Rockwell Automation comments on each section of the NEMA publication will appear after that section, with a "Comments" heading.

NEMA Standard Text

Scope

This Standards Publication is intended to provide general guidelines for the application, installation, and maintenance of solid-state control in the form of individual devices or packaged assemblies incorporating solid-state components. The emphasis of the guidelines is personnel safety. Applicable NEMA standards and product related instructions should be carefully followed.

Comments: Scope

The scope of this Allen-Bradley Publication (SGI-1.1) is identical to the scope of NEMA Standards Publication No. ICS 1.1, quoted above.

Section 1: Definitions

Electrical Noise – Unwanted electrical energy that has the possibility of producing undesirable effects in the control, its circuits and system. Electrical noise includes Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI).

Electrical Noise Immunity – The extent to which the control is protected from a stated electrical noise.

Electromagnetic Interference (EMI) – Electromagnetic disturbance that manifests itself in performance degradation, malfunction, or failure of electronic equipment. (IEC)

Off-State Current – The current that flows in a solid-state device in the off-state condition.

Off-State Condition – The conditions of a solid-state device when no control signal is applied.

On-State Condition – The condition of a solid-state device when conducting.

Radio Frequency Interference (RFI) – RFI is used interchangeably with EMI. EMI is a later definition that includes the entire electromagnetic spectrum, whereas RFI is more restricted to the radiofrequency band, generally considered to be between 10k and 10G Hz. (IEC)

Surge Current – A current exceeding the steady state current for a short time duration, normally described by its peak amplitude and time duration.

Transient Overvoltage – The peak voltage in excess of steady state voltage for a short time during the transient conditions (e.g., resulting from the operations of a switching device).

Section 2: General Authorized Engineering Information

General

(Sections 2 through 5 are classified as Authorized Engineering Information 11-15-1984.) Solid-state and electro-mechanical controls can perform similar control functions, but there are certain unique characteristics of solid-state controls which must be understood.

In the application, installation and maintenance of solid-state control, special consideration should be given to the characteristics described in 2.1 through 2.7.

General: Comments

Solid-state devices provide many advantages such as high speed, small size, and the ability to handle extremely complex functions. However, they differ from electromechanical devices in the basic operating characteristics and sensitivity to environmental influences. In addition, solid-state devices exhibit different failure mechanisms when overstressed.

The comments which follow are intended to provide additional information to help the reader better understand the operating characteristics, environmental limitations, and failure modes of industrial equipment that incorporates solid-state technology. Those who select, install, use, and service such equipment should apply that knowledge to make appropriate decisions that will optimize the performance and safety of their applications.

2.1 Ambient Temperature

Care should be taken not to exceed the ambient temperature range specified by the manufacturer.

Comments: 2.1 — Ambient Temperature

Temperature of the air immediately surrounding an open solid-state device is the ambient temperature -which must be considered. When equipment is installed in an enclosure, the enclosure internal air temperature is the ambient temperature which must be considered. Solid-state component manufacturers usually publish the component failure rate for an ambient temperature of 40º C. A useful rule of thumb is: The failure rate of solid-state components doubles for every 40º C rise in temperature.

This rule of exponential increases in failure rate is a strong incentive for the user to keep the ambient temperature as low as possible.

See also sections 3.6.1, and 3.6.2.

2.2 Electrical Noise

Performance of solid-state controls can be affected by electrical noise. In general, complete systems are designed with a degree of noise immunity. Noise immunity can be determined through tests such as described in 3.4.2. Manufacturer recommended installation practices for reducing the effect of noise should be followed.

Comments: 2.2 —Electrical Noise

Solid-state devices are generally more susceptible to electrical noise interference than their electromechanical counterparts. The reasons are straightforward. The operating mechanism for electromechanical devices requires a deliberate input of electrical energy that can be converted into a sustained mechanical force that is strong enough to close the hard contacts and maintain the closure for the duration on the ON cycle. Most random electrical noise signals lack the energy content to produce that magnitude of mechanical force. The operating mechanism for solid-state devices is totally different. The deliberate electric energy input is used to disturb the placement of the electrically charged particles within the molecular structure. This molecular displacement changes the electrical characteristic from that of an insulator to that of a conductor or vice versa. The required energy level is very low. In addition, a sustained signal is not required for components such as SCRs, triacs, and logic gates because these types are self-latching. Most random electrical noise signals are of the momentary low-energy type. Since it is difficult to separate deliberate signals from random noise, the devices are thereby more susceptible. This is cause for special concern regarding the electrical environment and possible need for noise rejection measures. See sections 3.4, 3.4.1, 3.4.2, and 3.4.3.

2.3 Off-State Current

Solid-state controls generally exhibit a small amount of current flow when in the off-state condition. Precautions must be exercised to ensure proper circuit performance and personnel safety. The value of this current is available from the manufacturer.

Comments: 2.3— Off-State Current

Off-state current is also referred to as leakage current in the literature. A solid-state "contact" is a solid block of material that is switched from ON to OFF by a change internally from a conductor to an insulator. Since a perfect insulator does not exist, there is always some leakage current present as long as voltage is applied to the device. The presence of leakage current indicates that OFF does not mean OPEN. The reader is warned that simply turning a solid-state device OFF does not remove the possibility of a shock hazard. Solid-state and electromechanical devices used as inputs to solid-state controls must be compatible with the solid-state equipment with which they are used. Solid-state devices have inherent off-state current, as explained in the preceding paragraph. Electromechanical devices may also permit a small amount of current to flow when the device is in the "open" position due to poor insulation characteristics, which may be subject to further deterioration with age and use. An example is a switching device that employs a carbon brush in contact with an insulating segment of the switch in the off-state, such that a conductive film may be deposited by the brush on the insulating segment. Any input device that could produce an erroneous signal of sufficient magnitude to cause a malfunction of the solid-state equipment, such as unintended turn ON or inability to turn OFF, should not be used with solid-state controls.

See also section 3.5.2.

2.4 Polarity

Incorrect polarity of applied voltages may damage solid-state controls. The correct polarity of solid-state controls should be observed.

Comments: 2.4 —Polarity

In some instances incorrect polarity can cause damage to controlled equipment or unintended actuation of outputs. This could result in personal injury due to an unexpected response of the controlled equipment or process.

See also section 3.3.2.

2.5 Rate of Rise-Voltage or Current

(DV/DT or DI/DT) Solid-state controls can be affected by rapid changes of voltage or current if the rate of rise (DV/DT and/or DI/DT) is greater than the maximum permissible value specified by the manufacturer.

Comments: 2.5 —Rate of Rise-Voltage or Current (DV/DT or DI/DT)

The DV/DT rating specifies the maximum rate at which voltage may be applied to the power terminals of a solid-state device. Voltage applied at a rate exceeding the DV/DT rating can switch the device ON without an input signal being applied. Electrical noise with high frequency content is one source of rapidly changing voltage.

Another common source of high DV/DT is an inductive load that is switched off faster than the stored energy can be dissipated. This fast switching produces “inductive kick voltages” that might exceed the DV/DT limit.

The DI/DT rating specifies the maximum rate at which current flow may be increased when switching from OFF to ON. Currents that increase faster than the DI/DT rating cause localized hot spots due to current crowding in a small area until the entire cross section can become conductive.

This results in gradual degradation of the device. Subsequent operations generally result in over dissipation and short circuit failures even under normal load conditions. The most common situations for high DI/DT are low load impedance, or capacitance loads.

Manufacturers of solid-state equipment usually include internal means to limit the rate of rise of voltage and current. Nonetheless, the user should be aware that additional external means may be necessary to adjust to the specific conditions of some installations.

2.6 Surge Current

Current of a value greater than that specified by the manufacturer can affect the solid-state control. Current limiting means may be required.

Comments: 2.6 — Surge Current

The manufacturer may specify allowable surge current. Common practice is to specify the peak sinusoidal current that can be allowed for one-half cycle at line frequency. The intent behind this practice is to give the user information for selecting an appropriate fuse or other current limiting means.

Applications that require short-term overcurrent capability (e.g., motor starting) must observe the manufacturers restrictions on the number of times the device can be subjected to overcurrent in a specified time interval. The user should be aware that this specification may vary depending upon whether the conditions call for hot starts or cold starts. Hot start means that the solid-state component is at or near the normal operating temperature due to previous operation history when the overcurrent condition occurs. Cold start means that the solid-state component is at or below 40º C when the overcurrent condition occurs.

2.7 Transient Overvoltage

Solid-state controls may be affected by transient overvoltages which are in excess of those specified by the manufacturer. Voltage limiting means should be considered and may be required.

Comments: 2.7 — Transient Overvoltage

Solid-state devices are especially sensitive to excessive voltage. When the peak voltage rating is exceeded, even for a fraction of a second, permanent damage can occur. The crystalline structure of the device may be irretrievably altered and the device may no longer be able to turn OFF.

The external symptom of this situation is exactly the same as that of an electromechanical device with welded contacts.

Minimum Holding Current

Another characteristic of concern is the minimum holding current requirement for triacs and SCRs. When the load current falls below the minimum value, typically 25...100 mA, the triac or SCR ceases conduction and passes only off-state current until again triggered. Thus, it may not be possible for the circuit to turn on or conduct full-load current for very light loads. In these instances, a load resistor called a bleeder resistor may be connected to the output to provide the minimum load. In some equipment special circuitry is provided to overcome this problem.

Section 3: Application Guidelines

3.1 General Application Precautions

3.1.1 Circuit Considerations

The consequences of some malfunctions such as those caused by shorted output devices, alteration, loss of memory, or failure of isolation within components or logic devices, require that the user be concerned with the safety of personnel and the protection of the electronics.

It is recommended that circuits which the user considers to be critical to personnel safety, such as "end of travel" circuits and "emergency stop" circuits, should directly control their appropriate functions through an electromechanical device independent of the solid-state logic. Such circuits should initiate the stop function through deenergization rather than energization of the control device. This provides a means of circuit control that is independent of system failure.

Comments: 3.1.1 —Circuit Considerations

The predominant failure mode of solid-state devices is in the ON condition. This failure mode and the other types of failures mentioned in the NEMA Standard are the reasons for the precautions that are recommended for safetycritical circuits on systems that control potentially hazardous processes or machine operations. Alternatively, if solid-state is used for circuits designated as safety-critical, the circuits should be designed to provide safety equivalent to the recommended "hard-wired" electromechanical circuits. In such cases consideration should be given to techniques such as: redundancy, feedback loops, diagnostics, interlocking and read-only memory for critical parts of a program.

De-energization rather than energization of the control device should be specified for STOP circuits so broken wires or corroded contacts do not go undetected. E-stop push buttons or pull cords should be installed at appropriate locations on a machine to provide operators with a rapid and convenient means for removing power from devices that control machine motion.

3.1.2 Power Up/Power Down Considerations

Consideration should be given to system design so that unsafe operation does not occur under these conditions since solid-state outputs may operate erratically for a short period of time after applying or removing power.

Comments: 3.1.2 Power Up/Power Down Considerations

Response of a system during power up/power down can create hazards not encountered during normal operation. Erratic operation of solid-state outputs due to the changing voltage of DC power supplies during start up is one example. To avoid unpredictable outputs, many power supplies incorporate a power turn-on time delay circuit. This allows power supply output voltage to reach its specified value before being applied to solid-state logic and output circuits. If this protection is not part of the DC supplies for a system, a timing circuit external to the power supply can be added to delay the application of power to output devices.

Removing all power or losing all power from a system simultaneously usually does not result in a hazard since the power for machine operation is also being removed. However, when power other than electrical power is being controlled, a power interlock circuit may be required to protect against unexpected machine motion. Power interlocks with automatic shutdown should be included if erratic or hazardous operation results due to loss of one power supply in a system with multiple supplies.

Automatic power supply sequencing should be employed in systems that require the application or removal of power in a specific sequence. If the STOP or E-STOP sequence normally employs dynamic braking, alternative safeguards, such as automatic mechanical braking upon loss of power, should be provided if coasting stops are hazardous.

If hazardous operation can result from unexpected restoration of power during a power outage or a system shutdown, the system should include a feature that requires a deliberate operator action before power is reapplied to the system.

3.1.3 Redundancy and Monitoring

When solid-state devices are being used to control operations, which the user determines to be critical, it is strongly recommended that redundancy and some form of checking be included in the system. Monitoring circuits should check that actual machine or process operation is identical to controller commands; and in the event of failure in the machine, process, or the monitoring system, the monitoring circuits should initiate a safe shutdown sequence.

Comments: 3.1.3 Redundancy and Monitoring

The normal operating mechanism for solid-state components depends upon a deliberate electrical signal input altering the internal molecular structure of the semiconductor material.

Unfortunately, spurious input signals may also alter the internal molecular structure without any means for external detection that this has happened. Therefore, solid-state devices are subject to malfunction due to random causes that are undetectable. Because of this, redundancy and monitoring are the most highly recommended means for counteracting this situation.

When redundancy is used, dissimilar components not susceptible to common cause failure should be used for the redundant elements if a common cause could produce simultaneous failure of those elements in a dangerous mode.

A “safe shutdown sequence” can involve much more than disconnecting electrical power for some machinery and processes. Examples include machines with high inertia and hazardous access points, processes that become unstable at shutdown unless a specific sequence is followed, etc. The control system for such applications should be configured to deal with the particular hazard(s) through use of special features such as automatic transfer of control functions to redundant devices in the event of failure of primary controls; alarm circuits and diagnostics to signal and identify failures that require repair in order to maintain redundancy; emergency power sources with automatic transfer upon loss of primary power source; or other appropriate features.

3.1.4 Overcurrent Protection

To protect triacs and transistors from shorted loads, a closely matched short circuit protective device (SCPD) is often incorporated. These SCPDs should be replaced only with devices recommended by the manufacturer.

Comments: 3.1.4 —Overcurrent Protection

Even a closely matched short-circuit protective device (SCPD) will generally protect a solid-state device only against shorted loads, an accidental short to ground, or a phase-to-phase short. Depending upon the application, additional protective measures may be needed to protect the solid-state devices against small to moderate overcurrents. Consult with the manufacturer if necessary.

3.1.5 Overvoltage Protection

To protect triacs, SCRs and transistors from overvoltages, it may be advisable to consider incorporating peak voltage clamping devices such as varistors, zener diodes, or snubber networks in circuits incorporating these devices.

Comments: 3.1.5 — Overvoltage Protection

See section 2.7.

3.2 Circuit Isolation Requirements

3.2.1 Separating Voltages

Solid-state logic uses low level voltage (e.g., less than 32V DC) circuits. In contrast, the inputs and outputs are often high level (e.g., 120V AC) voltages. Proper design of the interface protects against an unwanted interaction between the low level and high level circuits; such an interaction can result in a failure of the low voltage circuitry. This is potentially dangerous. An input and output circuitry incorporating effective isolation techniques (which may include limiting impedance or Class 2 supplied circuitry) should be selected.

Comments: 3.2.1 —Separating Voltages

For specifications of Class 2 circuitry, refer to Article 725 of the National Electrical Code, NFPA 70.

3.2.2 Isolation Techniques

The most important function of isolation components is to separate high level circuits from low level circuits in order to protect against the transfer of a fault from one level to the other.

Isolation transformers, pulse transformers, reed relays, or optical couplers are typical means to transmit low level logic signals to power devices in the high level circuit. Isolation impedance means also are used to transmit logic signals to power devices.

Comments: 3.2.2 — Isolation Techniques

In addition to utilizing the various components discussed in the left column, specific wiring techniques should be applied to assure separation of power circuit wires from logic circuit wires. If at all possible, logic wires should be run in a conduit that is segregated for that purpose only. Multiple conductors in a shielded cable is an appropriate substitute for separate conduits. Another common practice is to run the logic signals through twisted pairs of wire. Regardless of the circumstances, wires carrying logic signals should never be wrapped in the same bundle with wires that carry power signals.

3.3 Special Application Considerations

3.3.1 Converting Ladder Diagrams

Converting a ladder diagram originally designed for electromechanical systems to one using solid-state control must account for the differences between electromechanical and solid-state devices. Simply replacing each contact in the ladder diagram with a corresponding solid-state "contact" will not always produce the desired logic functions or fault detection and response. For example, in electromechanical systems, a relay having a mechanically linked normally open (N.O.) and normally closed (N.C.) contact can be wired to check itself. Solid-state components do not have a mutually exclusive N.O.-N.C. arrangement. However, external circuitry can be employed to sample the input and "contact" state and compare to determine if the system is functioning properly.

Comments: 3.3.1 —Converting Ladder Diagrams

The example cited in this section of the NEMA Standard illustrates only one of a number of reasons for special care in converting an electromechanical (relay) ladder diagram to a programmable controller (PC) program. Some other basic considerations are:

A PC program is an instruction to the PC's central processing unit to allow it to perform the logic functions and sequences for a particular application. Typically, the PC's logic level components are electrically isolated from the actual input, sensor and actuator devices, as contrasted with electromechanical controls which usually include contacts and coils of the actual plant floor devices in the control schematic. Therefore a PC program normally functions as open-loop control, unless feedback loops from the plant floor devices to separate inputs of the PC are provided and programmed to cause corrective action if inconsistencies are detected.

Programmers of PC systems should evaluate functional and safety implications of all control paths and provide appropriate feedback arrangements as needed.

In an electromechanical implementation of a ladder diagram, power is available to every rung at all times, so that the logic of the various rungs is executed continually and simultaneously, limited of course by the operating delays inherent in the electromechanical devices. By contrast, a typical PC examines the status of input devices (I/O scan), then executes the user program in sequence (program scan), then changes outputs accordingly in the next I/O scan. Therefore, the sequential order of a PC program can be of more importance and significance than in its electromechanical counterpart, particularly when special instructions such as "immediate" inputs or outputs are programmed as some PC's permit. Also, differences in response characteristics of components, differences in system architecture, and the scan time associates with a PC system can combine to change timing characteristics of a circuit significantly. In particular, care must be taken in handling momentary or rapidly changing inputs to a PC system which might be missed between scans. Simple transfer of a ladder diagram without consideration of these characteristics of PC's may produce unintended and possibly hazardous results. Programmers should consult the user's manual in order to understand the characteristics of the particular PC being used, and provide appropriate features in the program to accommodate them.

Another concern is the operating mode of devices connected to input terminals. Input signals must be arranged so loss of signal due to a broken wire or corroded contact does not go undetected and create a hazardous condition. In particular, stop functions should be initiated by opening a normally closed external circuit rather than closing a normally open circuit even though the system is capable of being programmed to accept either type of input.

The considerations described in this section apply to the creation of "new" programs as well as conversion of existing ladder diagrams.

3.3.2 Polarity and Phase Sequence

Input power and control signals should be applied with polarity and phase sequence as specified by the manufacturer. Solid-state devices can be damaged by the application of reverse polarity or incorrect phase sequence.

Comments: 3.3.2 —Polarity and Phase Sequence

Additionally, incorrect polarity or phase sequence connection may cause erratic response by solid-state controls, with potential hazards to personnel. Frequently, such a system contains a detection circuit that illuminates an indicator when incorrect phase sequence is applied. Phase sequence may be corrected by interchanging any two system input power leads. It is advisable to check rotation of motors whenever input power leads are disconnected and reconnected in a system.

3.4 Planning Electrical Noise Rejection

The low energy levels of solid-state controls may cause them to be vulnerable to electrical noise. This should be considered in the planning stages.

3.4.1 Assessing Electrical Environment

Sources of noise are those pieces of equipment that have large, fast changing voltages or currents when they are energized or de-energized, such as motor starters, welding equipment, SCR type, adjustable speed devices and other inductive devices. These devices, as well as the more common control relays and their associated wiring, all have the capability of inducing serious current and voltage transients on their respective power lines. It is these transients which nearby solid-state controls must withstand and for which noise immunity should be provided.

An examination of the proposed installation site of the solid-state control should identify equipment that could contaminate power lines. All power lines that will be tapped by the proposed solid-state control should be examined for the presence, severity, and frequency of noise occurrences. If found, system plans should provide for the control of such noise.

Comments: 3.4.1 — Assessing Electrical Environment

Noise can also occur in the form of electromagnetic radiation, or due to improper grounding practices. Section C.3.4.3 explains these forms of noise and precautionary measures that should be taken for protection against them.

In many instances a system may begin to malfunction some time after it has been installed and is working properly. This may be due to recent installation of new equipment capable of inducing noise into presently operating systems. Thus, it is not sufficient to merely evaluate a system at the time of installation. Periodic rechecks should be made, especially as other equipment is moved, modified, or newly installed. When installing a solid-state system, it is wise to assume various noise sources exist and install the system to guard against possible interference.

3.4.2 Selecting Devices to Provide Noise Immunity

Installation planning is not complete without examination of the noise immunity characteristics of the system devices under consideration. Results of tests to determine relative immunity to electrical noise may be requested from the manufacturer. Two such standardized tests are the ANSI (C37.90a-1974) Surge Withstand Capability Test and the NEMA (ICS.1-1983) noise test referred to as The Showering Arc Test. These are applied where direct connection of solid-state control to other electromechanical control circuits is intended. Circuits involving analog regulating systems or high speed logic are generally more sensitive to electrical noise; therefore, isolation and separation of these circuits is more critical.

Further information on electrical noise and evaluation of the severity of noise may be found in ANSI/IEEE Publication No. 518-1982.

Where severe power line transients are anticipated or noted, appropriate filters such as commercially available line filter, isolation transformers, or voltage limiting varistors, should be considered.

All inductive components associated with the system should be examined for the need for noise suppression.

Comments: 3.4.2 —Selecting Devices to Provide Noise Immunity

Inductive devices are capable of generating high voltage transients when switched off. In addition to possibly causing damage to solid-state devices by exceeding the semiconductor voltage rating, the high voltage transient can be coupled to other portions of a system where it appears as noise. Fortunately, it is fairly easy to limit the effects of this type of noise with some form of suppression device. When necessary, in addition to suppression devices often provided in solid-state equipment, an external suppressor should be connected as close as possible to the source of the transient for maximum attenuation.

NOTE: A surge suppressor increases drop-out time of an electromechanical device.

3.4.3 Design of Wiring for Maximum Protection

Once the installation site and power conductors have been examined, the system wiring plans that will provide noise suppression should be considered.

Conducted noise enters solid-state control at the points where the control is connected to input lines, output lines, and power supply wires.

Input circuits are the circuits most vulnerable to noise. Noise may be introduced capacitatively through wire to wire proximity, or magnetically from nearby lines carrying large currents. In most installations, signal lines and power lines should be separate. Further, signal lines should be appropriately routed and shielded according to manufacturer's recommendations.

When planning system layout, care must be given to appropriate grounding practice. Because design differences may call for different grounding, the control manufacturer's recommendations should be followed.

C.3.4.3 Design of Wiring for Maximum Protection

Noise can also occur in the form of electromagnetic radiation. Examples include radio frequency (RF) energy emanating from portable transceivers (walkie-talkie) and fixed station transmitters of various types. Close coupling is not required; the various lines entering the system act as receiving antennas. Tests described in 3.4.2 may not be sufficient to demonstrate noise immunity to radio frequency signals. Variations in building construction and equipment installation make it impossible for equipment manufacturers to perform meaningful tests of radio frequency sources. RF fields are affected by concentrating masses of metal such as steel beams, piping, conduit, metal enclosures, and equipment used in production such as fork lift trucks and products being transported on conveyors.

If the installation site will be subjected to this type of noise, thorough testing should be performed to assure that the solid-state system has sufficient noise immunity for the expected levels of radio frequency energy. Corrective measures should be taken if necessary. These include shielding of solid-state circuits and/or connected wiring and the establishment of restrictions to provide safe operating distances between the solid-state equipment and the RF sources.

Grounding practices in industry are frequently misunderstood and often ignored. Poor grounding can lead to many problems in solid-state systems. Intentionally grounding one circuit conductor of any electrical supply system is widely accepted and is generally required by electrical codes. However, the non-current carrying parts of a system which enclose equipment and conductors must also be grounded. In addition to complying with various codes and standards, proper equipment grounding achieves several desirable objectives:

1. It reduces the potential difference between conductive surfaces to minimize electric shock hazard exposure for personnel.

2. It provides a path for passage of fault current to operate protective devices in the supply circuit.

3. It attenuates the electrical noise and transients that can reach enclosed equipment and also reduces the electrical noise which the equipment can contribute to its surroundings.

3.5 Countering the Effects of Off-State Current

3.5.1 Off-State Current

Solid-state components, such as triacs, transistors, and thyristors, inherently have in the off-state a small current flow called "off-state current".

Off-state current may also be contributed by devices used to protect these components, such as RC snubbers.

Comments: 3.5.1 — Off-State Current

See section 2.3.

3.5.2 Off-State Current Precautions

Off-state currents in a device in the off-state may present a hazard of electrical shock and the device should be disconnected from the power source before working on the circuit or load.

Comments: 3.5.2 — Off-State Current Precautions

The off-state current of a power switching device such as a solid-state motor controller can be lethal. Simply switching off power via a stop push button in a control circuit is not a sufficient precaution, since off-state current will continue to flow through solid-state devices which remain connected to the supply. Good practice requires disconnection of all power from equipment before working on or near exposed circuit parts. (See NFPA 70E, Part II.)

It should not be assumed that a shock hazard does not exist simply because a solid-state circuit operates at low voltage levels. Standing on a wet floor or working in a damp location can lower a person's body impedance to the extent that off-state current from low voltage also presents an electrical shock hazard.

If it is necessary to work on energized equipment, the guidelines detailed in section 5.2 for Preventive Maintenance should be followed. In addition to the specific procedures for personnel safety, care is needed when making measurements in energized systems. First, there is a possibility of damage to delicate instruments due to off-state current. Second, the off-state current can lead to false conclusions when using sensitive instruments to check for "contact continuity."

Precautions should be taken to prevent the off-state current of an output device which is in the off-state from energizing an input device.

When a device (solid-state or electromechanical) that can produce a leakage current in the off-state is used to provide the input to a solid-state control, the precautions explained in section C.2.3 apply.

3.6 Avoiding Adverse Environmental Conditions

3.6.1 Temperature

Solid-state devices should only be operated within the temperature ranges specified by the manufacturer. Because such devices generate heat, care should be taken to see that the ambient temperature at the device does not exceed the temperature range specified by the manufacturer.

The main source of heat in a solid-state system is the energy dissipated in the power devices. Since the life of the equipment can be increased by reducing operating temperature, it is important to observe the manufacturer's "maximum/minimum ambient temperature" guidelines, where ambient refers to the temperature of the air providing the cooling. The solid-state equipment must be allowed to stabilize to within the manufacturer's recommended operating temperature range before energizing control functions.

When evaluating a system design, other sources of heat in the enclosure which might raise the ambient temperature should not be overlooked. For example, power supplies, transformers, radiated heat, sunlight, furnaces, incandescent lamps, and so forth should be evaluated.

In instances where a system will have to exist in a very hot ambient environment, special cooling methods may have to be employed. Techniques that are employed include cooling fans (with adequate filtering), vortex coolers, heat exchanges, and air conditioned rooms.

Over-temperature sensors are recommended for systems where special cooling is employed. Use of air conditioning should include means for prevention of condensing moisture.

Comments: 3.6.1 — Temperature

Operation above the maximum rated temperature will usually result in many failures in a short time. Nuisance type malfunctions can also be encountered as a result of elevated ambient temperature. These malfunctions, when they occur, are usually temporary and normal operation resumes when temperatures are lowered.

Some solid-state devices temporarily cease to function when ambient temperature is below their minimum rated operating temperature. Operation in cold environments should be avoided or heaters should be installed in the equipment enclosures to bring the system up to the minimum specified operating temperature before applying power to the system.

Air circulating in a non-ventilated enclosure with equipment operating will be at a higher temperature than the room in which it is installed. A temperature differential of 10...20º C can be expected in a typical industrial installation. *See also section 2.1.*

3.6.2 Contaminants

Moisture, corrosive gases and liquids, and conductive dust can all have adverse effects on a system that is not adequately protected against atmospheric contaminants.

If these contaminants are allowed to collect on printed circuit boards, bridging between the conductors may result in malfunction of the circuit. This could lead to noisy, erratic control operation, or at worst, a permanent malfunction. A thick coating of dust could also prevent adequate cooling on the board or heat sink, causing malfunction. A dust coating on heat sinks reduces their thermal efficiency.

Preventive measures include a specially conditioned room or a properly specified enclosure for the system.

Comments: 3.6.2 — Contaminants

Modules for solid-state systems usually consist of electronic devices mounted on printed circuit boards with relatively close spacing between conductors. Moisture in the form of humidity is one of the atmospheric contaminants which can cause failure. If moisture is allowed to condense on a printed circuit board, the board metallizations could "electroplate" across the conductor spacings when voltage is applied. In low-impedance circuits, this conductive path would immediately burn open, then reform to be burned open again. This action can lead to erratic operation. In high impedance circuits, a short circuit may appear resulting in a permanent malfunction. Specifications for equipment often include a relative humidity exposure limit, but appropriate precautions should be taken to prevent condensation. Failures due to moisture are often accelerated in the presence of corrosive gases or vapors. These increase the conductivity of the moisture layer allowing electromigration to occur more rapidly and at lower potentials.

3.6.3 Shock and Vibration

Excessive shock or vibration may cause damage to solid-state equipment. Special mounting provisions may be required to minimize damage.

Comments: 3.6.3 — Shock and Vibration

Solid-state systems usually have good resistance to shock and vibration since they contain no moving parts. However, at relatively high levels of shock or vibration, circuit boards may disengage from mating connectors if not restrained sufficiently. Circuit boards can crack, components can come out of sockets or component leads can break loose from a solder connection to the board. Mounting position is usually of little significance to solid-state devices except in instances where air flow is required for cooling.

3.7 The Need for Education - Knowledge Leads to Safety

Planning for an effective solid-state circuit requires enough knowledge to make basic decisions that will render the system safe as well as effective.

Everyone who works with a solid-state control should be educated in its capabilities and limitations. This includes in-plant installers, operators, service personnel, and system designers.

Section 4: Installation Guidelines

4.1 Installation and Wiring Practice

4.1.1

Proper installation and field wiring practices are of prime importance to the application of solid-state controls. Proper wiring practice will minimize the influence of electrical noise, which may cause malfunction of equipment.

User and installers should familiarize themselves with the follow installation and wiring instructions in addition to requirements of all applicable codes, laws, and standards. The manufacturer of the device or component in question should be consulted whenever conditions arise that are not covered by the manufacturer's instructions.

4.1.2

Electrical noise is a very important consideration in any installation of solid-state control. While wiring practices may vary from situation to situation, the following are basic to minimizing electrical noise:

1. Sufficient physical separation should be maintained between electrical noise sources and sensitive equipment to assure that the noise will not cause malfunctioning or unintended actuation of the control.

2. Physical separation should be maintained between sensitive signal wires and electrical power and control conductors. This separation can be accomplished by conduits, wiring trays, or as otherwise recommended by the manufacturer.

3. Twisted-pair wiring should be used in critical signal circuits and noise producing circuits to minimize magnetic interference.

4. Shielded wire should be used to reduce the magnitude of the noise coupled into the low level circuit by electrostatic or magnetic coupling.

5. Provisions of the 1984 National Electrical Code [1] with respect to grounding should be followed. Additional grounding precautions may be required to minimize electrical noise. These precautions generally deal with ground loop currents arising from multiple ground paths. The manufacturer's recommendations should be followed.

[1] Available from National Fire Protection Association, Batterymarch Park, Quincy, MA 02269

Comments: 4.1.2

A great deal of effort goes into the design of solid-state equipment to achieve a reasonable degree of noise immunity. Filters, shielding, and circuit design are all used. It is, however, impossible to design equipment which is impervious to every form of noise found in the industrial setting.

When installing a system using solid-state technology it is wise to assume that electrical noise exists and install the equipment in accordance with the recommended guidelines to minimize problems.

See also section 3.4.1.

4.2 Enclosures

Suitable enclosures and control of the maximum operating temperature, both of which are environmental variables, may be needed to prevent malfunction of solid state control.

The manufacturer's recommendations should be followed for the selection of enclosures, ventilation, air filtering (if required), and ambient temperature. These recommendations may vary from installation to installation, even within the same facility.

Comments: 4.2 — Enclosures (Cooling and Ventilating)

NEMA Standards Publication No. 250 (please reference the latest edition), classifies enclosures by type number and specifies their design test requirements.Suitable enclosures and control of the maximum operating temperature, both of which are environmental variables, may be needed to prevent malfunctions of solid-state control.

See also sections 2.1 and 3.6.1.

4.3 Special Handling of Electrostatic Sensitive Devices

Some devices may be damaged by electrostatic charges. These devices are identified and should be handled in the special manner specified by the manufacturer.

NOTE: Plastic wrapping material used to ship these devices may be conductive and should not be used as insulating material.

Comments: 4.3 — Special Handling of Electrostatic Sensitive Devices

Many problems due to electrostatic discharge (ESD) occur due to handling of modules during installation or maintenance.

In addition to specific guidelines provided by an equipment supplier, the following general guidelines can help reduce damage due to ESD.

1. Use a grounding bracelet if possible to minimize charge build-up on personnel.

2. Handle a module by the edges without touching components or printed circuit paths.

3. Store modules with ESD sensitive components in the conductive packaging used for shipping the modules. Also, use conductive packaging when returning static sensitive modules for repair.

4.4 Compatibility of Devices with Applied Voltages and Frequencies

Prior to energization, users and installers should verify that the applied voltage and frequency agree with the rated voltage and frequency specified by the manufacturer.

NOTE: Incorrect voltage or frequency may cause a malfunction of, or damage to the control.

4.5 Testing Precautions

When testing solid-state control, the procedures equipment should be electrically equivalent to that recommended by the manufacturer for the test procedure. A low impedance voltage tester should not be used.

High voltage insulation tests and dielectric tests should never be used to test solid-state devices. If high voltage insulation of field wiring is required, solid-state devices should be disconnected. Ohmmeters should only be used when and as recommended by the equipment manufacturer.

Testing equipment should be grounded; if it is not, special precautions should be taken.

Comments: 4.5 —Testing Precautions

Make-do test devices such as incandescent lamps or neon lamps should not be used for checking voltages in solid-state systems. Incandescent lamps have low impedance; the low impedance of these devices can effectively change a voltage level from a logic "1" condition to a logic "0" condition when attempting to make a measurement. Unexpected machine motion can result if an output to a controlled device is energized as a result. Neon lamps do not respond to voltages typically used in logic circuits (e.g., 32V DC or less). Use of a neon lamp tester could lead to false conclusions about the voltage level present in a circuit.

High input impedance meters are required to obtain accurate voltage measurements in high impedance circuits. Unless otherwise specified by the manufacturer, a meter with an input impedance of ten megohms or greater is recommended for making voltage measurements. The meter must also have sufficient sensitivity to measure logic level voltages; some meters do not respond to low voltages.

4.6 Startup Procedures

Checks and tests prior to startup and startup procedures recommended by the manufacturer should be followed.

Comments: 4.6 —Startup Procedures

Startup procedures can provide important benefits for safety with new installation, or after modifications or repairs. A "dry run" under controlled conditions can verify proper installation and functioning of the control system before it is turned over to operating personnel.

Many programmable solid-state systems have the capability for simulating operation in a mode known as "test" mode or "dry run" mode. These modes allow a user to check a program and correct obvious programming errors with outputs disabled. Unexpected machine motion and possible damage to workpieces and equipment is thus avoided. These modes can also be used to verify proper system operation after a repair.

Many programmable systems provide capability for "force on" and "force off" of inputs and outputs. Use of these functions can reduce troubleshooting and maintenance time by enabling personnel to bypass certain operations without physically operating switches on a machine. Care must be taken when using "force" functions to avoid exposing personnel to hazardous machine motions or process operations.

For controllers operating a machine tool or robot, running a part program at a fraction of the programmed operating speed with a workpiece of soft material is considered "good practice". This allows an operator to observe possible interference of tooling with the part and make corrections to the program. A workpiece of soft material such as wood, plastic, or machinable wax will minimize risk of tool damage if there is a tool crash with the workpiece.

Section 5 : Preventive Maintenance and Repair Guidelines

5.1 General

A well-planned and executed maintenance program is essential to the satisfactory operation of solid-state electrical equipment. The kind and frequency of the maintenance operation will vary with the kind and complexity of the equipment as well as with the nature of the operating conditions. Maintenance recommendations of the manufacturer or appropriate product standards should be followed.

Useful reference publications for setting up a maintenance program are NFPA 70B-1983, Maintenance of Electrical Equipment, and NFPA 70E-1983, Electrical Safety Requirements for Employee Workplaces.

5.2 Preventive Maintenance

The following factors should be considered when formulating a maintenance program:

1. Maintenance must be performed by qualified personnel familiar with the construction, operation, and hazards involved with the control.

2. Maintenance should be performed with the control out of operation and disconnected from all sources of power. If maintenance must be performed while the control is energized, the safety related practices of NFPA 70E should be followed.

3. Care should be taken when servicing electrostatic sensitive components. The manufacturer's recommendations for these components should be followed.

4. Ventilation passages should be kept open. If the equipment depends upon auxiliary cooling, e.g., air, water, or oil, periodic inspection (with filter replacement when necessary) should be made of these systems.

5. The means employed for grounding or insulating the equipment from ground should be checked to assure its integrity (see 4.5).

6. Accumulations of dust and dirt on all parts, including on semiconductor heat sinks, should be removed according to the manufacturer's instructions, if provided; otherwise, the manufacturer should be consulted. Care must be taken to avoid damaging any delicate components and to avoid displacing dust, dirt, or debris in a way that permits it to enter or settle into parts of the control equipment.

7. Enclosures should be inspected for evidence of deterioration. Accumulated dust and dirt should be removed from the top of the enclosures before opening doors or removing covers.

8. Certain hazardous materials removed as part of maintenance or repair procedure (e.g., polychlorinated biphenyls (PCBs) found in some liquid-filled capacitors) must be disposed of as described in Federal regulations.

C.5.2 Preventive Maintenance

Lithium batteries are frequently used for memory backup in solid-state equipment due to their excellent shelf life and high energy-to-weight ratio. Lithium is a highly reactive metal that can cause burns if there is contact with skin. The batteries are sealed so there is seldom a problem of contact with lithium as long as reasonable care is exercised when handling them. They should only be used in their intended application and not subjected to rough handling. When batteries are replaced in equipment, the batteries removed should be disposed of in accordance with supplier's instructions.

The Department of Transportation has certain regulations that prohibit shipment of equipment with batteries installed if the batteries contain 0.5 gram or greater of lithium. The batteries must be removed from equipment and shipped separately in a container approved by the Department of Transportation. Additional Department of Transportation restrictions apply to the shipment of lithium batteries.

NEMA Standards Publication No. ICS 1.3 - 1986, Preventive Maintenance of Industrial Control and System Equipment, is recommended for personnel responsible for maintenance of equipment.

5.3 Repair

If equipment condition indicates repair or replacement, the manufacturer's instruction manual should be followed carefully. Diagnostic information within such a manual should be used to identify the probable source of the problem, and to formulate a repair plan. The level of field repair recommended by the manufacturer should be followed.

When solid-state equipment is repaired, it is important that any replacement part be in accordance with the recommendations of the equipment manufacturer. Care should be taken to avoid the use of parts which are no longer compatible with other changes in the equipment. Also, replacement parts should be inspected for deterioration due to "shelf life" and for signs of rework or wear which may involve factors critical to safety.

After repair, proper startup procedures should be followed. Special precautions should be taken to protect personnel from hazards during startup.

Comments: 5.3 — Repair

Follow manufacturer's instructions exactly when replacing power semiconductors mounted on heatsinks since improper installation may become the source of further difficulties. Torque semiconductors or bolts retaining semiconductors to the value specified using a torque wrench.

Too much pressure against a heatsink can damage a semiconductor while too little can restrict the amount of heat transferred from the semiconductor to the heatsink and result in operation at higher temperature with decreased reliability.

Exercise care when removing modules from a system during maintenance. Failed modules are frequently returned to the manufacturer for repair. Any physical damage sustained during removal may result in more expensive repair or render the module unrepairable if damage is too great.

Modules with electrostatic sensitive components should be handled by the edges without touching components or printed circuit conductors. Use packaging material supplied with the replacement module when shipping the module to the manufacturer for repair.

When the scope of repairs exceeds the manufacturer's recommendations for field repair, the module(s) should be returned to the manufacturer for repair. Doing so will help to ensure that only properly selected components are used, and that all necessary hardware and firmware revisions are incorporated into the repair. Failure to make necessary updates may result in safety, compatibility or performance problems which may not become apparent for some time after the repaired module has been placed back in service. When firmware is protected by copyright law, updates can be provided legally only by the manufacturer or licensee.

See also section 4.3.

5.4 Safety Recommendations for Maintenance Personnel

All maintenance work should be done by qualified personnel familiar with the construction, operation, and hazards involved with the equipment. The appropriate work practices of NFPA 70E should be followed.

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