The application of relay coil suppression with DC relays

This application note has been written in response to the numerous application problems resulting from improper relay coil suppression. The typical symptom is random "tack" welding of the normally-open contacts when switching an inductive load or a lamp load with high inrush current.

The Need for Transient Suppression

When an electromechanical relay is de-energized rapidly by a mecanical switch or semiconductor, the collapsing magnetic field produces a substantial voltage transient in its effort to disperse the stored energy and oppose the sudden change of current flow. A 12VDC relay, for example, may generate a voltage of 1,000 to 1,500 volts during turn-off. With the advent of modern electronic systems, this relatively large voltage transient has created EMI, semiconductor breakdown, and switch wear problems for the design engineer. It has thus become common practice to suppress relay coils with other components which limit the peak voltage to a much smaller level.

Types of Transient Suppression Utilized with Relays

The basic techniques for suppression of transient voltages from relay coils are shown in Figure 1. As observed here, the suppression device may be in parallel with the relay coil or in parallel with the switch used to control the relay. It is normally preferred to have the suppression parallel to the coil since it can be located closer to the relay (except in the case of PC board applications where either may be used).

When the suppression is in parallel with the relay coil, any of the following may be used.

A. A bilateral transient suppressor diode that is similar in V-I characteristics to two zener diodes connected cathode to cathode (or anode to anode).

B. A reverse-biased rectifier diode in series with a zener diode such that their anodes (or cathodes) are common and the rectifier prevents normal current flow.

C. A metal-oxide-varistor (MOV).

D. A reversed-biased rectifier diode in series with a resistor.

E. A resistor, when conditions permit its use, is often the most economical suppression.

F. A reversed-biased rectifier diode.

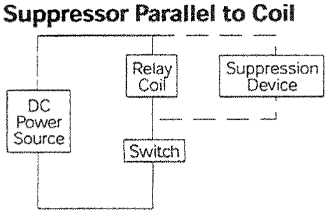
G. A resistor-capacitor "snubber". Generally the least economical solution and no longer considered a practical solution.

H. A bifilar wound coil with the second winding used as the suppression device. This is not very practical since it adds significant cost and size to the relay.

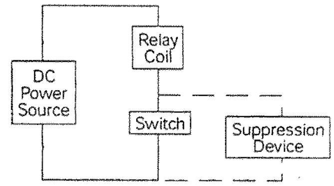
Suppression used in parallel with the switching element is likely to be either a zener diode or a resistor-capacitor "snubber". The comments associated with the "parallel to coil" application are also applicable to this circuit.

Figure 1 - Schematic for Relay Coil Suppression

Suppressor Parallel to Coil



Suppressor Parallel to Switch



Effects of Coil Suppression on Relay Dynamics and Life

Even though the use of coil suppression is becoming more significant, relays are normally designed without taking the dynamic impact of suppressors into account. The optimum switching life (for normally-open contacts) is therefore obtained with a totally unsuppressed relay and statements of rated electrical life are usually based on this premise. The successful "breaking" of a DC load requires that the relay contacts move to open with a reasonably high speed.

A typical relay will have an accelerating motion of its armature toward the unenergized rest position during drop-out. The velocity of the armature at the instant of contact opening will play a significant role in the relay's ability to avoid "tack welding" by providing adequate force to break any light welds made during the "make" of a high current resistive load (or one with a high in-rush current). It is the velocity of the armature that is most affected by coil suppression. If the suppressor provides a conducting path, thus allowing the stored energy in the relay's magnetic circuit to decay slowly, the armature motion will be retarded and the armature may even temporarily reverse direction. The reversing of direction and re-closing of the contacts (particularly when combined with inductive loads) often leads to random, intermittent "tack welding" of the contacts such that the relay may free itself if operated again or even jarred slightly.

Based upon the impact on armature motion and optimizing for normally-open contacts, the best suppression method is to use a silicon transient suppressor diode. This suppressor will have the least effect on relay drop-out dynamics since the relay transient will be allowed to go to a predetermined voltage level and then permit current to flow with a low impedance. This results in the stored energy being quickly dissipated by the suppressor. Transient suppressor diodes are available as bi-directional components and permit the relay to be non-polarized when installed internally. Note that if a uni-directional transient suppressor is used, a rectifier diode must be placed in series with it to block normal current flow and it has little advantage over the use of a zener diode. The transient suppressor should be selected such that its pulse energy rating exceeds any anticipated transient such as coil turn-off or motor "noise" found in the application.

A metal-oxide-varistor will provide results similar to those of transient suppressor diode, but will have a higher "on-state" impedance and will thus allow a higher voltage to be developed. As an example, a 33 volt transient suppressor diode may have a "clamping" voltage between 30 and 36 volts. In comparison, a 33 volt MOV will likely clamp the relay at 45 to 55 volts (based on a typical automotive relay with 130 mA coil current). When the additional voltage is no problem, an MOV may save cost over the transient suppressor diode and will also provide a non-polarized relay.

The use of a reversed-biased rectifier diode in series with a zener diode will provide the best solution when the relay can be polarized. This suppression is often recommended by Siemens Electromechanical Components (SEC) for use in automotive circuits. The impact on release dynamics is minimal and poses no loss of reliability. This is normally a low-cost method and the only design precaution is to select a zener with an appropriate breakdown voltage and impulse power specifications adequate for the relay in its application. In printed circuit board applications with transistors used as relay drivers, the zener diode can be placed "across" the transistor; that is, for a common emitter circuit, cathode connected to collector and anode connected to the emitter (the series rectifier diode is not used in this type of circuit).

A reversed-biased rectifier in series with a resistor may be used successfully with some relays when maximum load switching capacity is not required. Care must be taken to use a resistor large enough in value to quickly dissipate the relay's stored energy but yet stay within the desired peak voltage transient. The required resistor value may be approximated from the following equation:

$$R = V_{peak}/I_{coil}$$

where:

R = resistor value in Ohms
V_{peak} = peak transient voltage permitted
I_{coil} = steady-state relay coil current

The actual voltage peak observed will be lower than calculated by this formula due to energy losses in the resistor. When using this type of suppression it is best to consult the relay manufacturer for recommended values.

A resistor may also be used by itself as a transient suppressor when the additional power dissipation and resulting heat generated by the resistor can be tolerated. In most situations, this will provide the least expensive suppression method (assuming the resistor value can be properly sized to minimize its impact on relay performance). This method is normally recommended by SEC when the application requirements permit.

Many engineers use a rectifier diode alone to provide the transient suppression for relay coils. While this is cost effective and fully eliminates the transient voltage, its impact on relay performance can be devastating. Problems of unexplained, random "tack welding" frequently occur in these systems. In some applications, this problem is merely a minor nuisance or inconvenience and the controller or operator will cycle the relay until the proper response is obtained. In many applications; however, the first occurrence may cause a complete system failure or even present a hazardous situation. It is important that these systems be designed with another method of relay suppression.

To illustrate the impact of various coil suppression on the relay response time, consider the following data that was recorded using an automotive ISO type relay with a 55 ohm coil and with 13.5VDC applied to the coil.

Suppression Technique	Drop-out Time (ms)	Theoretical Transient	Recorded Transient
Unsuppressed	1.5		-750
Diode & 24V Zener	1.9	-24.8	-25
680Ω Resistor	2.3	-167	-120
470Ω Resistor	2.8	-115	-74
330Ω Resistor	3.2	-81	-61
220Ω Resistor	3.7	-54	-41
100Ω Resistor	5.5	-24.6	-22
82Ω Resistor	6.1	-20.1	-17
Diode	9.8	-0.8	-0.7

Suggested Methods for Relay Coil Suppression

From the standpoint of physics, the suggested technique for relay coil transient suppression is to use a reversed-biased rectifier diode and series zener diode in parallel with the relay coil. This permits the relay to have optimum release dynamics and normally-open contact life. Such suppression may be incorporated easily into the circuitry for printed circuit board relays; however, when specifying suppression for a socket-mounted relay, this method may be less practical than using a resistor.

When the permissible transient voltage is large enough and power dissipation tolerable, the relay may be suppressed with a resistor. From the standpoint of a Failure Mode and Effects Analysis (FMEA), the resistor will provide less added risk of failure than the two diodes suggested above (provided that its value is high enough to avoid detrimental effects to the relay's release dynamics). It must be noted that the optimum resistor value for one type of relay will not necessarily be the right value for another type.

Now that we have provided suggested suppression techniques based on normally-open contact performance, we must add a qualifying comment concerning the normally-closed contacts. When the primary load is on the normally-closed contacts (and a small load or none on the normally-open), it may be desirable to use a rectifier diode alone as the relay suppression (or perhaps a rectifier diode and a lower value of series resistor). The retarded armature motion that adversely impacts normally-open contact performance will typically improve normally-closed contact performance. The improvement results from less contact bounce during closure of the normally-closed contacts. This results from the lower impact velocity created by the retarded armature motion and has been utilized in the past to improve normally-closed contact performance on certain relays.

Beware of Zero-Crossover Switching of Transformers

A zero-crossover solid-state relay may be the worst possible method of switching on a transformer or a highly inductive load. Evidence[1] has come to light that zero-crossover turn-on of such loads can cause a surge current of perhaps 10 to 40 **times** the steady state current, whereas turn-on at **peak** voltage results in little or no surge.

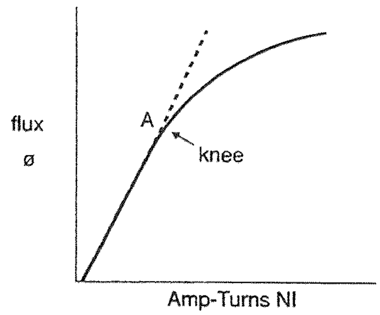


Figure 1

Surge currents of such magnitude can seriously shorten the life of the zero-crossover SSR, unless the SSR has a current rating well in excess of the load. They create EMI and RFI (all along the load line) which can destroy logic gates and cause unwanted turn-on of semiconductor switches. Additionally, these surge currents create thermal and mechanical stress on the windings of the inductance and on the transformer core laminations. These stresses can lead to early failure of the device.

The cause of inrush currents of such magnitude is core saturation. Transformers are designed to operate below the knee of the saturation curve of the core material that is, below point A in figure 1. However, saturation does occur, and when it does, inductance decreases to a very low value. Impedance then drops to little more than the DC resistance of the primary circuit. (This can hold true for any saturable reactance.)

When an inductance whose core contains no remanent magnetism is initially energized at voltage peak, the rate-of-change of current (di/dt) generates maximum counter emf and, as shown in A of Figure 2, there is no flux surge. However, if voltage is applied at zero, cemf is minimal and "flux doubling" occurs, as shown in B of Figure 2. This flux doubling is the result of a current surge which can last for several half-cycles.

Remanent magnetism in the core can aggravate this surge condition. It is the nature of core material to retain magnetism to some degree after magnetizing voltage has been removed. If transformer primary voltage is reapplied at zero crossover and in such a direction that the increasing field supports remanent flux, a flux of $2ø_m + ø_r$ results (C of Fig. 2). This flux, of course, is entirely offset from zero, and the core is in deep saturation, as shown by the hysteresis curve in F of Figure 2. (D and E are the hysteresis curves for conditions A and B, respectively.) Inrush current, therefore, is many times normal, as shown in G of Figure 2, and can last for several half-cycles.

A 150 VA transformer has a 120 volt primary DC resistance of approximately 1.5 ohm, and a 500 VA transformer, a 120 volt primary resistance of approximately 0.3 ohm. One might think a 5 amp zero-crossover SSR would be more than sufficient to switch the current of the 150VA transformer. However, during core saturation, primary-winding inrush is 80 amps:

$$I = \frac{E}{R} = \frac{120}{1.5} = 80 \text{ amps.}$$

In the case of the 500 VA transformer, one might think a 10 amp SSR might suffice. But, during core saturation, primary current is 400 amps!

$$I = \frac{E}{R} = \frac{120}{0.3} = 400 \text{ amps.}$$

Under such conditions, the SSR is severely overloaded, and the transformer overheats. (Power expended in the primary during this 400 amp surge would be approximately 40 KVA.)

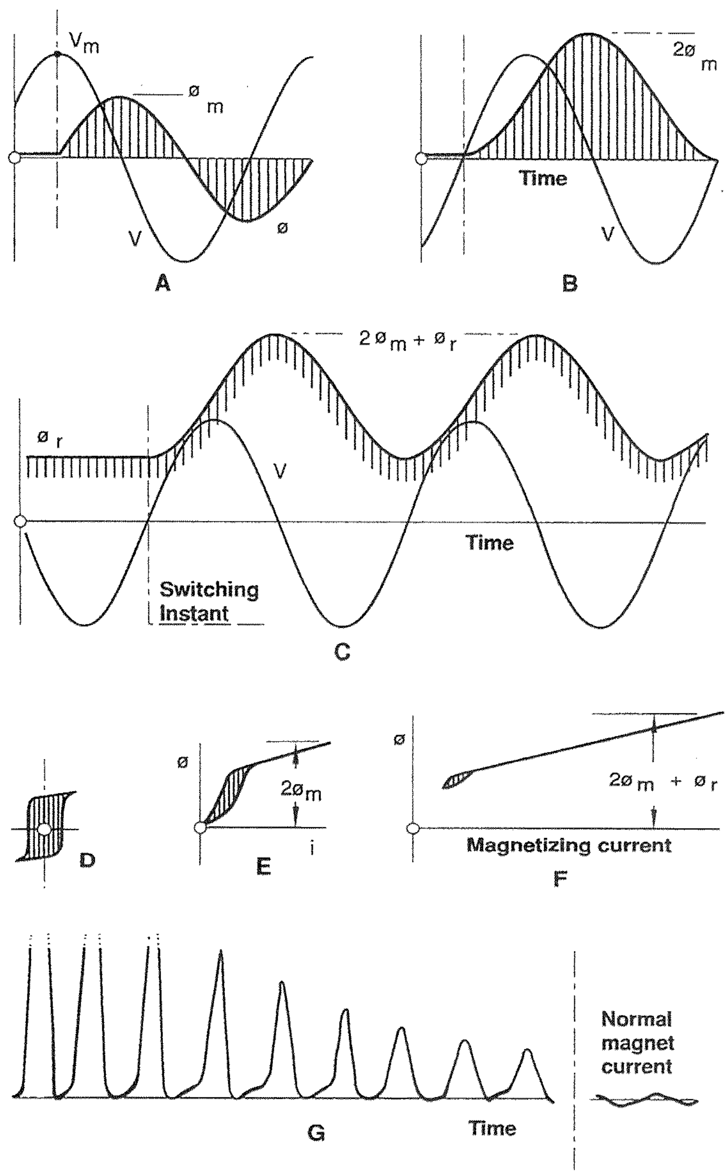


Figure 2

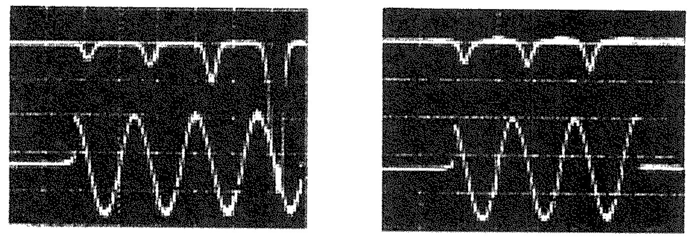
Figures 3 and 4 show the effect of a 90° turn-on SSR on transformer inrush current. In Figure 3A, the transformer secondary is open, and the primary is turned on near zero voltage. A first half-cycle inrush of 200 amps occurs (read scope tracing right to left). However, when that same transformer is turned on at peak voltage (Fig. 3B), inrush is just 17% greater than steady state current. That is, inrush if 7 amperes.

Figure 4 shows the oscillogram of the same transformer with the secondary connected to a 250 ohm resistor. As can be seen by comparing Figs. 3A and 4A, a loaded secondary has no appreciable effect on primary inrush current.

Surge currents such as those shown in Figures 3A and 4A can be destructive to a zero-crossover SSR.

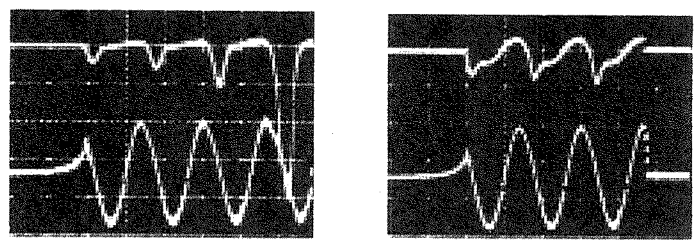
A "zero-crossover" SSR does not always turn on at precisely zero voltage. It takes perhaps a millisecond or more for the circuitry to react. Therefore, the load switch may not be fully on until load voltage is perhaps 15 to 20 volts. In this event, surge current isn't as great, but it is still potentially destructive. Also, a random turn-on SSR may, at times, turn on at or near zero cross-over. The best method of turning on transformers and other saturable, highly-inductive loads is by use of a peak voltage turn-on device. Turn-on at peak voltage results in minimal surge, if indeed any surge is present at all.

Zero-crossover SSRs are excellent switches for resistive capacitive, and slightly inductive loads. Even so, inrush current must be taken into consideration. That is, an incandescent lamp can pull a "cold-filament" inrush current of 10 to 20 times the steady-state "hot filament" current. A motor can pull a "locked rotor" current of perhaps 6 times its running current. And the inrush of a capacitor, or the inrush of a circuit in which significant stray capacitance is present, is limited solely by the DC resistance of the circuit.



A (10A / vert. div.) B (50A / vert. div.)

Figure 3: 150 VA transformer, unloaded secondary. Top tracing is primary current; bottom tracing is primary voltage (120VAC). (Read tracing from right to left.)



A (10A / vert. div.) B (50A / vert. div.)

Figure 4: 150 VA transformer, secondary connected across 250ohm resistor, 240VAC. Top tracing is primary current; bottom tracing is primary voltage (120VAC).

1. Reference material:
"Alternating Current Machines," Halsted Press, John Wiley & Son, *"Inductively Loaded SSRs Control Turn-On to Eliminate First-Cycle Surges,"* Electronic Design, March 15, 1979. *"Controlling Transformer Inrush Currents,"* EDN, July, 1966. *"The Great Zero Cross-over Hoax,"* NARM Proceedings, May, 1974.

Coil Suppression Can Reduce Relay Life

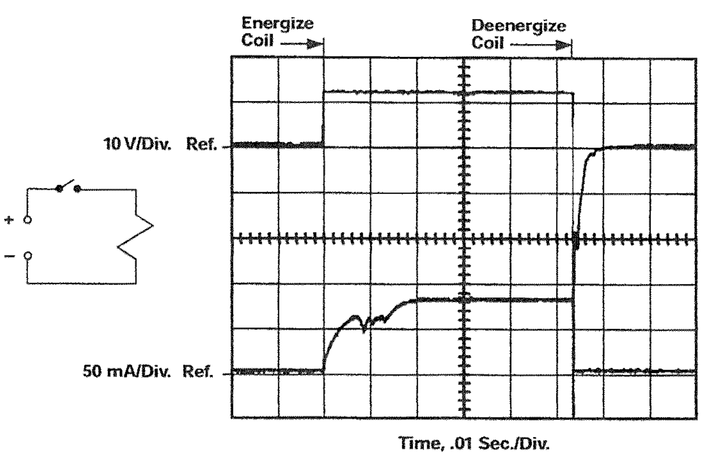
This application note deals with problems related to the methods used in deenergizing electromagnetic relay coils, particularly when a solid state switch is used, and how they affect relay life.

It is primarily concerned with the deenergization cycle of the relay, and discusses:

1) The armature and switching dynamics of the relay system upon coil deenergization.
2) How coil induced voltages occur.
3) Techniques for protecting the solid state switch.
4) The adverse effect of a simple coil suppression diode on relay switching dynamics and contact life.
5) The typical "sticking" between mating contacts and the reduced ability to break when using diode suppression.
6) How the addition of a Zener diode to the ordinary diode can provide both voltage suppression and reliable switching performance.

Relay deenergization or "drop-out" in typical clapper-type relays normally develops as follows: As the coil supply is interrupted, the magnetic flux decays to the point where the decreasing magnetic holding force (trying to keep the armature seated) drops below the spring forces (trying to unseat it), and armature opening commences. As armature opening continues, spring forces reduces according to the armature position; the countering magnetic force, however, reduces both with armature position and with decay of coil current (both of which reduce coil magnetic flux).As the electrical current in a relay coil is interrupted, an induced voltage transient of the order of hundreds or even thousands of volts may be generated across that coil as its magnetic flux, which is linked by the coil turns, collapses. This induced voltage, plus the coil supply voltage, as shown in Fig. 1, appears across the coil interrupting switch in a simple series switching circuit.

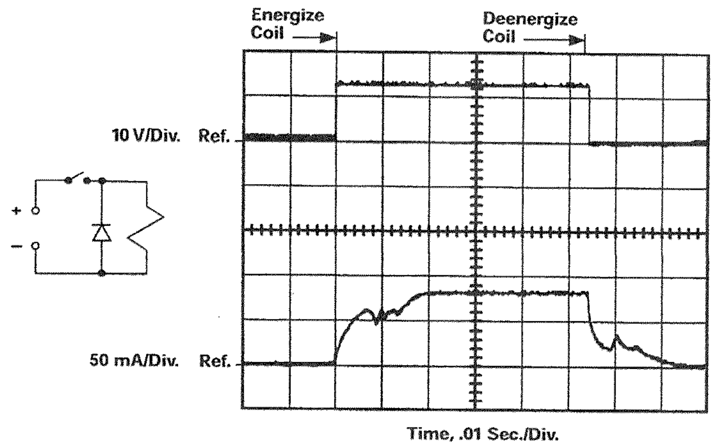
Figure 1– Operate & Release Dynamics Coil V & I, Typical DC Relay Without Diode



In today's logic control systems, a solid state switch is often used to operate a DC coil relay, and this switch is protected from coil deenergization induced voltages by various suppression techniques. These techniques are frequently effected by coil shunting means, designed to mitigate the suddenness of coil current interruption and resultant high rate of coil magnetic flux collapse.

One very common practice is to simply shunt the coil with a general purpose diode, placing the diode to block the source voltage and conduct with the reverse polarity of the coil induced voltage. This provides a path for the current flowing in the deenergized coil to be externally shunted back into the coil, limiting the magnitude of coil induced voltage to the forward drop of the diode, which the coil current, and resulting magnetic flux, slowly decay (see Fig. 2).

Figure 2– Operate & Release Dynamics Coil V & I, Typical DC Relay With Diode



This diode shunt provides maximum protection to the solid state switch, but may have very adverse effects on the switching capability of the relay. It is important to realize that the net force available to cause the armature to open is the difference between the magnetic restraining forces and the spring opening forces, that each of these is varying in a manner to cause the net force to vary both with time and armature position. It is this net force which gives rise to the armature system velocity and energy of momentum as it attempts to effect armature and contact spring transfer.

A slowly decaying magnetic flux (the slowest is experienced with a simple diode shunt across the coil) means the least net force integral available to accelerate the armature open. In fact, rapid loss of the opening forces supplied by stiff NO contact springs, coupled with slowly decaying magnetic forces, can actually cause a period of net force reversal where the armature velocity is slowed, stopped, or even momentarily reversed until the flux further decays, finally permitting available spring "return" forces to cause transfer to continue.

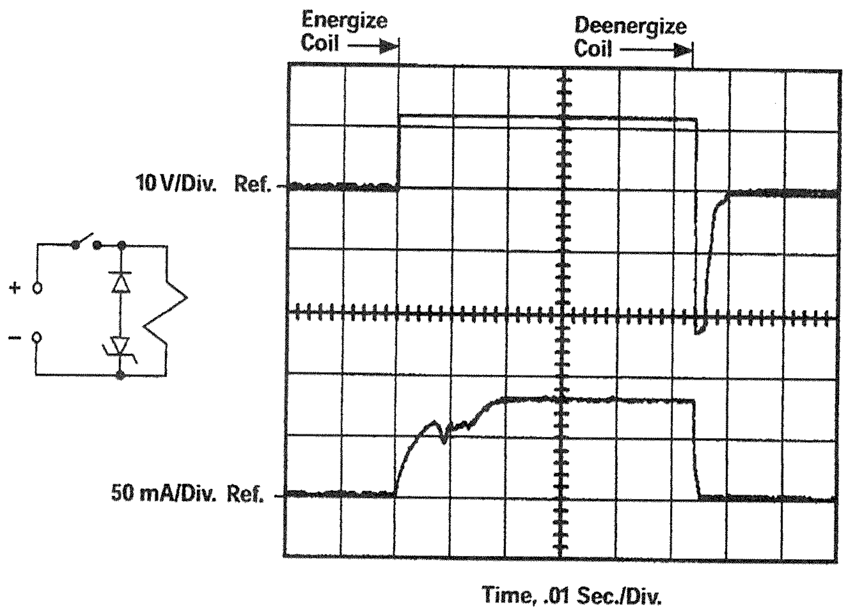
It is equally important to realize that when the contacts of a typical power relay make, connecting very fast rising (e.g., resistive) medium or high current loads to the voltage source, a minute molten interface occurs between the mating contacts, giving rise to a microweld or stick condition that must be separated at the next opening transfer.

The "stick" force is normally well within the ability of the net opening force, aided by the momentum of the moving armature, to break the stick and effect contact transfer. However, the loss or even reversal of armature velocity (under conditions of simple diode shunting as described above), and accompanying loss of armature momentum needed to help break the contact stick, can result in failure to break the stick, and a contact "weld" is experienced.

The more rapidly the coil current decays, the less the magnetic hold back, and thus the greater the armature momentum and contact stick "break-ability."

Obviously, this is optimized when **no** suppression is used. However, near optimum decay rate can be obtained by using a Zener diode in series with a general purpose diode. When the coil source is interrupted, the coil current is shunted through this series arrangement, maintaining a voltage equal to the Zener voltage (plus forward diode drop) until the coil energy is dissipated. This is illustrated in Fig. 3.

Figure 3– Operate & Release Dynamics Coil V & I, Typical DC Relay With Diode & 24V Zener



The Zener voltage value is chosen to limit the coil switch voltage to a level acceptable to the switch rating. This affords the best compromise both to coil switch protection and relay switching performance, and should be employed to assure maximum relay performance and reliability while providing protection to the control circuit from coil induced voltages.

It is normal industry practice to test relays and subsequently establish performance ratings without coil suppression. When application conditions require the suppression of coil induced voltages, it is recommended that the relay's performance be evaluated with the suppression that will be used.

Contact Arc Phenomenon

What precisely is an electric arc? How does it ignite and what causes it to extinguish? How does an arc affect the life of relay contacts?

These are some of the questions that we will discuss here. We hope to help you better understand how to obtain the longest life possible from relay contacts such as these.

But first, let's take a minute to define a few of the terms we'll be using.

First of all, "constriction" refers to the very first, tiny area of contact surface to make, and the very last point to break.

Melt Voltage is that amount of voltage that exists across the constriction which will cause a current sufficient to liquify the contact material at the constriction.

Arc Voltage is that amount of voltage that exists on contacts separated by a small gap that will cause an electric discharge across the gap.

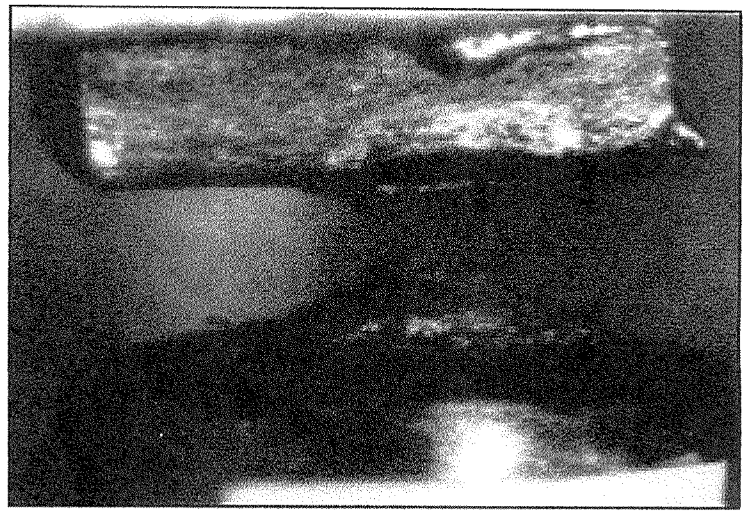
And, lastly, Arc Current is that amount of current necessary to just sustain an arc caused by the arc-voltage electric discharge.

Now, keep these terms in mind as we take you into the world of relay contacts—a fairly harsh environment. Let's take a microscopic look at the effects of contact arcing.

As you know, the end result of contact arcing is shortened contact life. Depending on the severity and duration of the arc, each time an arc ignites, contact erosion occurs. This erosion causes a loss of contact material which will result in one of two conditions.
Condition #1 is where so much material is lost from the contacts that

Condition #1

they fail to electrically close the load circuit. Condition #2 is where one contact loses so much material to the other contact that a spike-and-crater results.



Condition #2

Another result of severe arcing which may occur now and then is contact welding. Usually, though, when this happens, it is evidence that the relay has been misapplied in a circuit where voltage and/or current are much greater than that particular relay can handle.

Regarding a spike-and-crater condition, when the condition gets severe enough, the high spot—that is, the spike—may mechanically hang up on the rim of the crater. Then when the relay is deenergized, the contacts fail to open, and the load is in an uncontrolled-on condition. Needless to say, this is an undesirable situation.

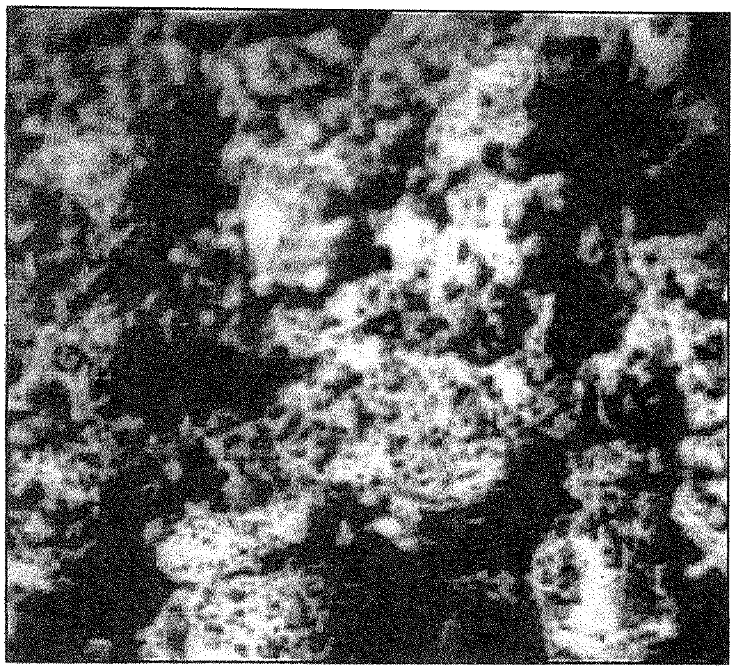
Typically, a spike-and-crater material transfer condition is associated with a direct current application. But we are beginning to notice that even in some alternating current applications, spike-and-crater material transfer is evident.This is because, in these applications, the relays are being operated in synchronization with the AC line voltage. This synchronization usually is the result of the synchronization to the AC line of the solid state logic or microcomputer circuitry that operates the relay. If synchronization just happens to occur at or near line voltage peak, then each time the relay contacts operate, they do so at or near either 170 volts or 340 volts, depending, of course, on whether line voltage is 120 or 240 volts.

If the application requires that the circuit clock be synchronized to the AC line, additional circuitry should be included to effect random operation of the relay. Or, synchronization might be set that the relay contacts open at or near current zero.

Just one further comment here regarding spike-and-crater material transfer. Don't automatically assume this type of transfer is the result of contact arcing. It may not be. Even in circuits in which no arc ignites, material transfer may occur. This is because the circuit voltage is greater than the melting voltage of the contact material and when the contacts just come together or just separate, the material melts, travels from the hotter contact, the anode, to the cooler contact, the cathode, and remains there. In an AC application where operation is truly random, material transfers first one way one time and the other way another time. The net result is no appreciable gain of material by either contact. But in a DC application or in an application where the relay is synchronized to the AC line, material transfer is always in the same direction and a spike-and-crater condition may result.

When an arc ignites, material transfer is from cathode contact to anode contact. Therefore, in any given operation of the contact, before an arc ignites, material transfers from anode to cathode, and then when the arc ignites, material transfers from cathode to anode. The amount of transfer is usually greatest during the arc. Keep in mind, though, as just explained—and this is **important**—in a truly random AC application, the net material gain of either contact is negligible, while in a DC application or in an application synchronized to the AC line, there may be significant material gain by one contact.

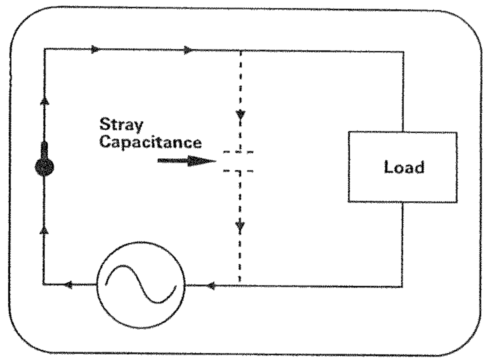
Now, let's take a look at just what happens on contact closure. If you could examine the surface of a relay contact under a high power microscope, you'd see that the surface is quite irregular, consisting of deep low spots and a lot of high spots— with some spots higher than the others.



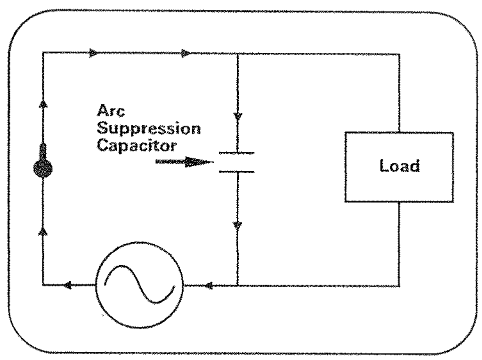
As the contacts just come together, the first high spot to make contact is subject to full load current. If load current is even a fraction of an ampere, the I^2R heat generated in this high spot instantly causes the high spot to melt and perhaps even boil. The air surrounding the high spot is superheated and begins to ionize by the loss of electrons. If I^2R energy is sufficient, the high spot may reach a temperature of 5,000 Kelvin or more and may explode, leaving superheated, ionized air and metallic ions in the gap between the contacts. Depending on contact material and the voltage stress on this air gap—that is, the contact voltage at the instant of the explosion—the ionized air gap may begin to conduct electron current from cathode to anode. This electric discharge between contacts is actually the beginning of an arc. If load current is in excess of the arc current rating of the contact material, the arc will contain sufficient energy to sustain itself. If not, the discharge between contacts will **not** cause arc ignition.

If an arc ignites, due to the Thompson effect there is a temperature gradient along the arc column, with the cathode being the hotter contact. That is, heat will flow from cathode to anode. The cathode spot in which I^2R heat is greatest may boil, thereby giving off atomic and even molecular emissions. These emissions are pulled through the arc column and deposited on the slightly cooler anode contact. This, of course, is the principle of arc wielding. All of this happens in perhaps ten nanoseconds or more as the contacts continue to move together.

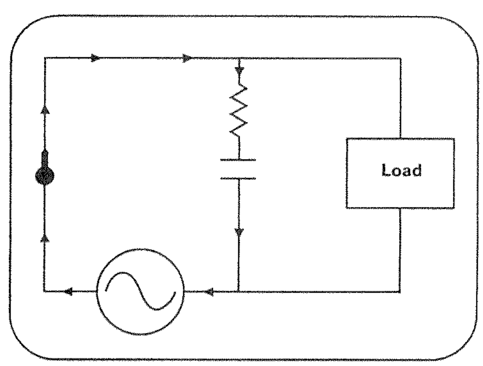
The arc exists until the next high spot or high spots make. Again, the heat in these high spots may cause them to melt. When they do, they begin to spread out, increasing the area of contact make. As the contacts move together forcefully, this liquified metal may spatter, resulting in a loss of material. As the molten metal between the contacts cools, the contacts are frozen together in the normal manner. Unlike the catastrophic weld which may occur when a relay is misapplied, this weld is weak and easily broken by the action of the relay spring forces when the relay is deenergized. Now, think back! What actually had to happen before the arc could ignite? Was load current or voltage responsible for the arc? Well, certainly the arc must have a medium through which to travel, and the ionized gap between the contacts is that medium. And certainly it was load current heating of a contact high spot which caused the ions. But it was the voltage that existed across the contact gap that resulted in arc ignition. This voltage need not be load voltage. It may be circuit voltage. That is, upon contact make, there may be a certain amount of capacitance in the circuit that will charge through the contacts.



Also, if an arc-suppression capacitor is used across the contacts, this capacitance will discharge itself through the relay contacts.



The discharge surge current may be hundreds of amperes for a few nanoseconds or more. To limit such discharge currents, an arc-suppression capacitor should have a certain amount of resistance in series with it. In circuits where there is no dedicated capacitance, however, there still may be sufficient stray capacitance to cause a momentary overcurrent upon contact make. This fact is often overlooked by many circuit designers.



An arc ignites in similar manner upon contact break. As the contacts begin to separate, less and less contact area carries load current. Load current begins to funnel into this constricted area and I^2R heat begins to increase. The very last point of contact melts and, as the contacts continue to separate, a thin bridge of molten metal is stretched between the contacts. The air in the gap begins to ionize. The I^2R energy in the bridge generates so much energy that the bridge literally explodes, showering the gap with metallic ions. Again, if contact voltage is sufficient, an arc will ignite.

Different contact materials have different arc voltage ratings. For fine silver, the arc voltage is 12 volts. For cadmium, it is 10 volts; and for gold and palladium it is 15 volts. Let's assume the contacts are fine silver. Within nanoseconds after the molten bridge explodes, if the material is silver and if circuit voltage is 12 volts or more, voltage breakover occurs. If circuit voltage is less than 12 volts, breakover cannot occur and there will be no arc.

When an arc ignites between separating contacts, it will be sustained as long as there is sufficient energy to feed it. As long as the arc exists, material transfer will continue. In a direct current application, the arc can be extinguished only by stretching it to such a length that its own impedance causes it to extinguish, or by opening the circuit at some other point. In many applications, though, the contact gap is wide enough that the arc will extinguish before the contacts have fully opened. It is for this reason that relays of a given contact rating will be rated for, say, 120 volts AC, but will have a considerably lower DC voltage rating—usually 28 or 30 volts DC. That is, the gap is wide enough that, given the periodic swing through zero of alternating current, any AC arc should quickly extinguish. But the gap would not be wide enough for a 110 volt DC arc to extinguish.

In an AC application, depending on the temperature of the ionized air, even though arc current decreases to zero every half-cycle, the arc may reignite after current zero. This is because positive ions still exist between the contacts and it doesn't require much energy to reignite the arc.

It has long been recognized that, compared with fine silver, silver-cadmium-oxide contacts yield superior life in the presence of an arc. One theory says that since oxide coated materials produce negative ions when heated sufficiently, the negative ions produced by silver-cadmium oxide cause early recombination of the positive ions after current zero. This recombination causes the arc to extinguish earlier and may prevent reignition after current zero. This would seem to indicate that in an AC application where arcing is to be expected, silver-cadmium-oxide contacts protected with an appropriate arc suppression method should yield good contact life. We won't get into arc suppression techniques here because that's the subject of another application note titled "Relay Contact Life." All we will say about arc suppression here is that appropriate suppression can result in lengthened contact life. Additionally, by suppressing the arc, electromagnetic interference—EMI, for short—is held to a minimum. EMI is the result of atomic action in the arc column. In an arc plasma, the surface of the contacts is bombarded by atoms, positive and negative ions and electrons, some of which may be accelerated by passing through the electric field, and some of which may cause secondary emission of electrons which may radiate energy across a wide spectrum of frequencies. By quenching the arc quickly, this action is held to a minimum. The result often is a considerably lessened amount of electro-magnetic and radio frequency interference.

In summation, to achieve the maximum life from arcing relay contacts, proper relay and contact application and the possible use of arc suppression are most important.

Beware of AC applications where the relay is synchronized to the AC line voltage. If synchronization is unavoidable, set the clock so that relay contact operation occurs at or near zero current.

And, when severe arcing conditions are expected, select a relay having silver-cadmium contact material.

Thank you for spending these past few minutes with us. We hope we've been able to help you better understand how to achieve the longest possible life from your relay contacts.

Determining Relay Coil Inductance

Relay users often desire to know the inductance of the relay coil they are using so they can determine the energy released by the coil upon deenergization.

Coil inductance with armature seated is greater than that when unseated. This is because inductance varies directly with incremental permeability (μ) and inversely with the length (ℓ) of the magnetic circuit path. The air gap in the magnetic circuit of an unseated armature both decreases μ and increases ℓ. Of course, the greater the inductance, the greater the energy released into the coil circuit upon deenergization.

Inductance also will vary with coil voltage, since permeability varies with magnetizing force which, in turn, is determined by coil voltage. For values most meaningful to the circuit designer, inductance should be measured under conditions that simulate actual relay service; that is, at rated voltage and current.

Inductance with armature seated represents actual application conditions at the instant coil power is removed. When coil power is removed, the coil generates a counter voltage, $-e = L(di/dt)$, which is fed back into the switch circuit. Depending on energy levels, this voltage surge may adversley affect the life or operational characteristics of the switch that controls the relay coil. (For methods to protect the switch, see "Coil Suppression Can Reduce Relay Life", 13C3264.)

The inductance of DC coils should be measured by the $L = tR$ method by use of an oscilloscope. This method requires the application of rated DC voltage to the coil while physically holding the armature seated. The value, t, is the time for coil current to increase to .623 of its steady state value, and R is the coil DC resistance in ohms as measured by an ohmmeter.

The inductance of AC coils may be determined by measuring coil voltage and current and actual power consumed by use of a wattmeter. The product of coil voltage and current is the "VA" in the following equation, "W" is the power as given by the wattmeter. R = measured DC resistance in ohms.

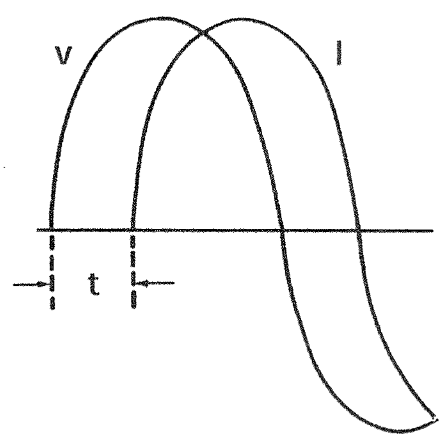
$$L = \frac{X_L}{2\pi f} = \frac{Z\sin\theta}{2\pi f} = \frac{(R/\cos\theta)\sin\theta}{2\pi f};$$

where $\theta = \cos^{-1}$ (W/VA).

If a wattmeter isn't available, inductance may be determined by use of a dual-trace oscilloscope, one input of which is fed by a current probe. In this method, rated voltage at the proper frequency is impressed on the coil, and the time displacement, t, of applied voltage and coil current is measured by the oscilloscope. Inductance is calculated as above, where:

$$\theta = \frac{360°t}{16.7\text{ ms}}$$

t = time in ms by which coil current lags coil voltage.



Electromechanical vs. Solid State Relay Characteristics Comparison

	Characteristics	EMR	SSR
General	Sensitivity to withstand misuse or misapplication	Good	Poor
	Sensitive to corrosion, oxidation, or contaminates	Yes	No
	Sensitive to shock, vibration or acceleration	Yes	No
	Sensitivity to radiation	Fair	Poor
	Package versatility	Good	Fair
	Cost per pole	Best	Fair
	Input TTL & CMOS (buffer) compatibility	Fair	Best
	Operate and release time	5-20 mS	.25-10 mS
	Compatibility of military/aerospace specs.	Good	Poor
	Ease of troubleshooting	Good	Poor
	Input to output isolation capability	4Kv	>4Kv
	Normal failure mode (output)	Open	Shorted
	Normal wearout mechanism	Contacts	LED
*Output Switching Capabilities	Physical size per pole	Best	Fair
	Available output contact forms	1A, 1B, 1C	1A, 1C, 2A, 4A
	Multipole capability from single input	Yes	Some
	Electrical life expectancy (operations)	>100K	>100 Million
	Capable of rapid duty cycle switching	Some	All
	Capable of AC & DC voltage switching	Yes	Some
	Capable of inductive load switching	Yes	Yes
	Capable of resistive load switching	Yes	Yes
	Capable of capacitive load switching	Yes	Yes
	Capable of low level load switching	Yes	Some
	Capable of dry circuit load switching	Yes	No
	Capable of coaxial load (RF) switching	Yes	No
	Capable of precision synchronous switching	No	Yes
	Capable of zero voltage turn-on/zero current turn-off	No	Yes
	Output contact off-state resistance	>1 M ohms	>20K ohms
	Output contact on-state resistance	<.05 ohms	<.1 ohms
	Output contact arcing	Yes	No
	Output contact bounce	Yes	No
	Level of EMI/RFI generated (emitted)	Large	Small
	Derating of output current required above T_A=25°C	No	Yes
	Heatsink required to switch maximum rated loads	No	Some
	Inrush surge current capability (ref. to max. rated current)	1-5 times	2-10 times
	On-state surge current capability (ref. to max. rated current)	1-5 times	2-10 times
	Sensitive to explosive environment	Yes	No
	Sensitivity to magnetic fields	Fair	Good
	Sensitive (susceptibility) to EMI/RFI false operation	No	Yes
	Sensitive to ESD (electrostatic discharge) turn-on	No	Yes
	Sensitive to overvoltage turn-on	No	Yes
	Sensitive to thermal turn-on	No	Yes
	Sensitive to dv/dt turn-on	No	Yes
	Sensitive to load di/dt turn-on	No	Yes

**Ability is highly application dependent*

Mounting, Termination and Cleaning of Printed Circuit Board Relays

Incorrect handling and mounting of printed circuit board relays can alter the relay's operational characteristics and result in premature relay failure. Additionally, recommended conductor widths and PC board cleaning procedures play an important part in assuring that the assembly will yield long, reliable service.

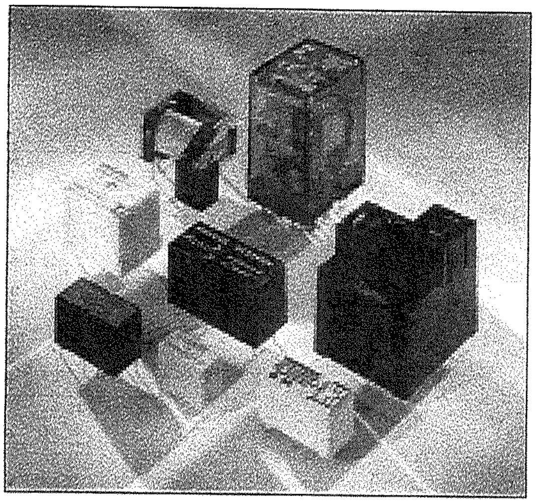


Figure 1. Tyco Electronics printed circuit board relays. Shown are miniature relays designed for switching signals as well as power relays capable of switching up to 30 amps.

PC Board Design and Relay Mounting:

— Avoid handling relay by the armature, contacts or terminals. This will prevent contamination and altering of contact-arm adjustments.

— Relays should be located away from semiconductors and other signal devices. This will reduce the effects of electromagnetic interference. Also, signal traces should be located away from relay traces.

— Relays controlled by solid state devices may require coil suppression. For more information refer to Application Note 13C3264, "Coil Suppression Can Reduce Relay Life."

— Position relays as close as possible to the connectors. This keeps PC board heat rise to a minimum.

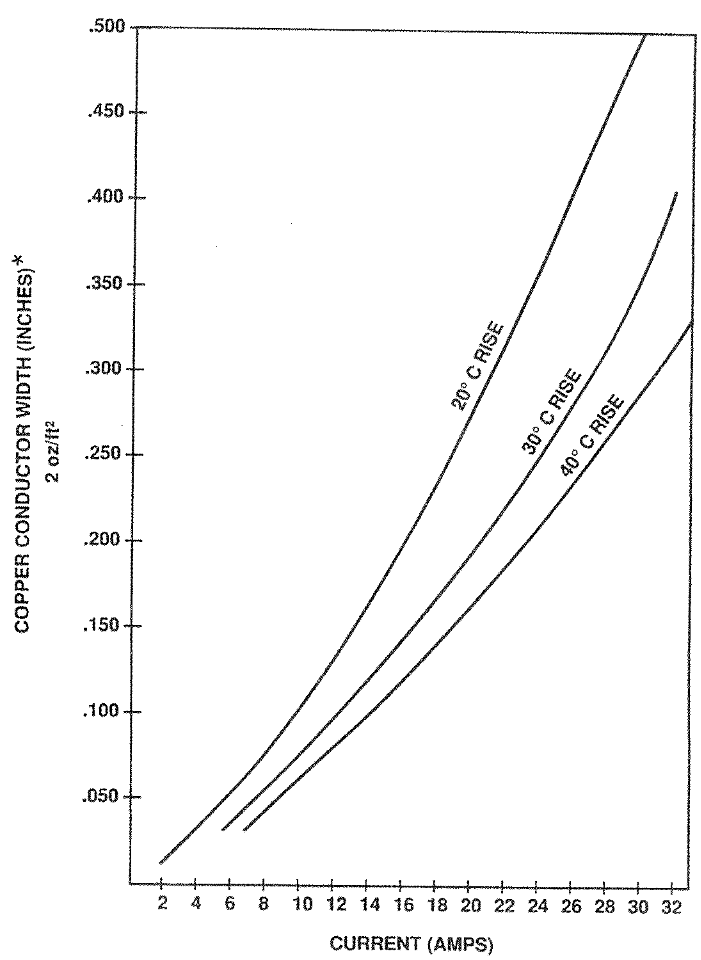
— UL/CSA spacings as required by the end-use application should be observed on PC board layout.

— Refer to data sheets for suggested PC board layout and recommended hole diameter.

Conductor Thickness:

The printed wiring must be at least as wide as that listed in Graph 1. Current through too small a trace will generate excessive heat, exceeding temperature ratings.

Graph 1. PC Board Temperature Rise Above Ambient (°C) as a Function of Conductor Width and Load Current



*** For the width of 1 oz/ft² (1.35 mils) copper, width = 2 X (width of 2 oz/ft²). If a double-sided PC board with plated-through holes is to be used, one-half of the required 1 oz/ft² or 2 oz/ft² copper width may be located on each side of the board.**

Wave Smoldering:

— A non-corrosive flux is recommended.

— Preheat the PC board as recommended by flux vendor. This not only improves solderability but also allows the relay to stabilize.

— Do not allow solder flux to infiltrate relay components.

— Wave soldering exposure time should be kept to a minimum. Do not solder to flow on top of the PC board.

— Air cool the PC board before cleaning. This allows the relay temperature to stabilize.

Cleaning:

Open and Dust Cover Relays

- Use only clean distillate spray to remove flux; not to exceed two minutes. Never immersion clean open or dust covered relays.
- Avoid aqueous solvents. Water may be trapped between coil windings, resulting in wire corrosion.
- Use only those solvents listed in Table 1 (or equivalents) as cleaning agents. Many cleaning solvents will cause the coil tape adhesive to loosen. Relays without coil tape may be cleaned with any solvent listed, except aqueous.
- Any solvent used to clean the PC board should itself be continuously distilled. Otherwise, the spray may distribute flux, oil or dissolved acids throughout the relay. This leads to contact problems and corrosion.

Plastic Sealed Relays

- Spray cleaning or immersion cleaning may be used to remove flux. Cleaning time should be limited to two minutes.
- Avoid thermal shock during the cleaning process. Excessive thermal or mechanical shock may damage the seal integrity.
- Use only those solvents listed in Table 1 (or equivalents) as cleaning agents.
- After an aqueous cleaning, use a clean water rinse to remove all cleaning agents.
- To insure maximum relay life on tape and tab enclosures, vent the relay after board cleaning and before the relay is put into service.

Table 1; Solvent Compatibility

Solvent		Spray Clean Only		Immersion Sealed
		Open	With Dust Cover	
Alcohols	Isopropyl	O	O	O
	Ethanol	O	O	O
	Methanol	O	O	O
Aqueous	Indusco 624, 1000 (a)	X	X	O
	Loncoterge 520, 530 (a)	X	X	O
	Hollis 310 (a)	X	X	O
Chlorinated	Alpha 564, 565	X	X	(b)
	Chlorosolve	X	X	(b)
	Trichlorethane	X	X	(b)
	Trichlorethylene	X	X	(b)
	Perchloroethylene	X	X	(b)
Fluorinated	Freon TF, TE, TES	O	O	O
	Freon TMS	O	O	O
	Freon TMC	X	O	(b)
	Alpha 1001, 1003	O	O	O
	Hydroflourocarbons	O	O	O

O = Acceptable
X = Not Recommended
(a) Strong caustic, acid or amine solutions are not to be used with open relays.
(b) Spray clean only; may attack enclosure or marking.

Operating DC Relays from AC and Vice-Versa

A relay coil is copper wire wound many times on and around a bobbin in which an iron core is situated. When a voltage of sufficient magnitude is impressed across the coil, the coil and core develop magnetism which attracts the armature. The armature, in turn, controls contact movement. Depending on the total length of the wire and its unit cross-sectional area, the coil exhibits a certain amount of resistance to the flow of electric current. According to Ohm's Law, for a given amount of resistance, current is directly proportional to voltage. That is:

$$I = \frac{E}{R}$$

where; **I** = current in amperes
E = voltage in volts
R = resistance in ohms

Thus, a 12V DC coil that has 120 ohms of resistance pulls 0.1 amp of current.

Some relay coils accept DC voltage, while others accept AC voltage. DC (direct current) voltage has a constant, unchanging value. At any given instant of time, a 12V DC power source measures exactly 12 volts (give or take a few tenths of a volt, normally). (See Fig. 1A)

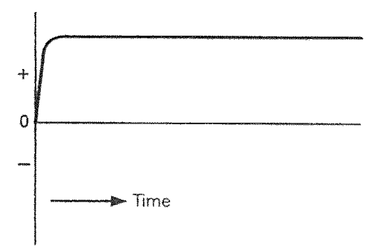


Fig. 1A - DC voltage waveform.

AC (alternating current) voltage, conversely, is constantly changing in value. As pointed out in lesson 2 of the Siemens Electromechanical Components self-study series, "Understanding Relays," at any given instant of time, the voltage on a 120V AC line, for example, is undergoing a change. (See Fig. 1B) That is, voltage begins at zero, increases to a

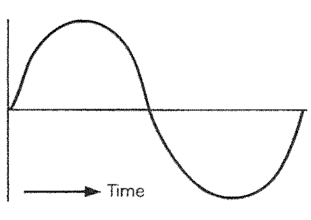


Fig. 1B - AC voltage waveform.

peak value, decreases to zero, crosses zero and increases to peak in the opposite direction, then decreases to zero again. This process continuously repeats.

Assume that this 120V AC is to be transformed to 12 volts and impressed across the 12V DC coil. A measure of coil current would show that considerably less than the current calculated by Ohm's Law would flow in the coil (and its associated circuit). This reduction in coil current is the result of the impedance the coil presents to the alternating current. (Impedance is a function of inductance, and is present only when alternating current flows.)

In order to operate its armature, a certain amount of power must be developed in the relay coil. Since power is the product of current-squared times resistance ($P = I^2R$), the amount of power developed in the coil would be considerably less than that required for proper relay operation. To develop the required power, coil voltage would have to be increased to that value where sufficient current flows.

In theory, then, AC can be used to operate a DC relay. In reality, however, doing so is impractical. Since alternating current decreases to zero every half-cycle (120 times per second for 60 cycle voltage), the relay armature tends to release every half-cycle. This continual movement of the armature not only causes an audible "buzz," but will cause the contacts to open and close as the armature moves.

In order to operate a relay from AC, relay manufacturers use a device known as a shader ring (or shader coil) on top of the core. (See Fig. 2). Because of the shader ring, the magnetism developed in part of the core lags somewhat the magnetism of the remainder of the core. That is, there is a slight phase displacement between the magnetism of part of the core and the remainder of the core. Thus, as unshaded-core magnetic energy decreases to zero every half-cycle, the magnetic energy decreases to zero every half-cycle, the magnetic energy still present in the shaded portion of the core holds the armature sealed. By the time the energy in the shaded portion decreases to zero, coil and unshaded-core magnetic energy have begun to increase once again as current increases in value.

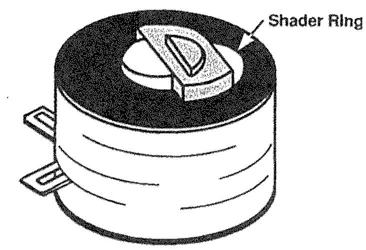


Fig. 2 - AC coils use a shader ring to prevent the relay armature from releasing as magnetic energy decreases to zero every AC half-cycle.

"Shading" the R10 Series (AC Coil) Relay

The R10 (and competitive) relays use a unique method of shading the coil. As shown in Fig. 3, when AC voltage on the top side of the coil goes negative, diode M1 conducts current through the bottom half of the coil.

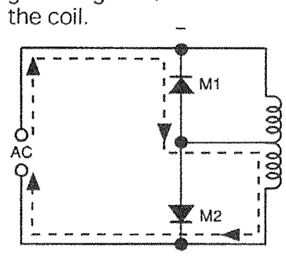


Fig. 3 - The R10 Series AC coils use rectifying diodes and a "dual coil" arrangement to prevent the armature from releasing every half-cycle.

Since M1 is in parallel with the top half of the coil, no current is present in the top half of the coil.However, as a result of magnetizing one half of the coil and the resultant core magnetism, magnetic energy is generated in the top half of the coil. This magnetic energy lags somewhat that of the conducting half of the coil and, as just described, serves to hold the armature seated when current decreases to zero.

When AC voltage reverses, diode M2 conducts and M1 turns off. Coil current is now present in the top half of the coil and generates magnetism of the same polarity as that remaining from the previous half-cycle. Thus, the armature has no chance to release. As before, the nonconducting part of the coil serves as a shader to hold the armature seated.A diode may be used in series with a relay coil, and serves to rectify the AC voltage. However, a diode should never be placed in parallel with the coil in an AC circuit. Doing so would result in the diode conducting, not the relay, as voltage swings negative on the diode. (Besides, the first time the diode conducts, it will be destroyed because there is nothing in series with it to limit current.)

DC on an AC Relay

Just as it is impractical to operate a DC relay from AC, it is likewise impractical to operate an AC relay from DC. However, in an emergency, an AC relay may be operated from DC—provided certain precautions are taken. The first precaution is to provide some type of a residual break between relay core and armature to prevent the armature from "sticking" as a result of any appreciable residual magnetism remaining in the core after coil power is removed. The second precaution that should be taken is to make sure the amount of DC voltage used is less than the AC voltage rating of the coil.

Regarding the residual break, AC relays are so constructed that when the armature is in its seated position, it physically (magnetically) touches the core. (On DC relays, a small copper pin in the armature effectively prevents the armature from coming in magnetic contact with the core.) As long as the AC relay is operated from AC voltage, there is no problem with residual magnetism holding the armature seated after release of coil power. But when an AC relay is operated from DC voltage, there is a danger that residual magnetism may hold the armature seated. At the very least, the presence of residual magnetism in the core causes a reduction in the dropout voltage of the relay.

To negate the effects of residual magnetism, a small piece of mylar tape may be stuck to the top of the AC relay core. This tape is extremely durable, and should last for perhaps hundreds (if not thousands) of operations. The tape should be .002" to .004" thickness.

Regarding the required reduction in coil voltage, consider the KR series relay coil. The 12V AC coil has a DC resistance of 24 ohms. According to Ohm's Law, 12 volts divided by 24 ohmsequals 0.5 ampere. However, as pointed out on the KR data sheet, the coil actually pulls just .168 ampere! (This is the result of coil impedance.) This .168 ampere causes the coil to develop sufficient power to perform its intended work. However, the 0.5 ampere would cause 6 watts of power to be developed. This is well in excess of the maximum allowed. As a result, the coil would overheat and wire insulation would burn off. Then the coil turns would short together. The coil would pull even more current, and finally burn out completely.

To use an AC coil on DC requires lowering the amount of DC voltage to that value where coil power is within maximum limits. Again consider the KR. The open-style unit has a maximum power rating of 4 watts. To determine the amount of DC voltage to use with a 12V AC coil having a DC resistance of 24 ohms:

$$P = \frac{E^2}{R}$$

$$4 = \frac{E^2}{24}$$

$$4 \times 24 = E^2$$

$$96 = E^2$$

$$\sqrt{96} = \sqrt{E^2}$$

$$9.8 = E$$

Thus, DC voltage cannot exceed 9.8 volts. Since the data sheet lists the pick up value when using DC voltage as 75% of rated value, the DC voltage in this example should not be lower than 7.35 volts.

When using rectified AC to operate any relay coil, it is best to use filtering. As shown in fig. 4A, AC that is rectified but unfiltered has voltage peaks and valleys—that is, maximum and minimum values. If the minimum values should be 75% or less of rated voltage, the armature might experience movements. As shown in Fig. 4B, filtering eliminates ripple. Thus, rectified and properly filtered AC will have no appreciable ripple.

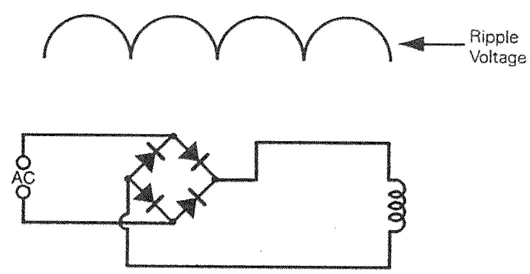


Fig. 4A - Rectified, unfiltered AC voltage has ripple present.

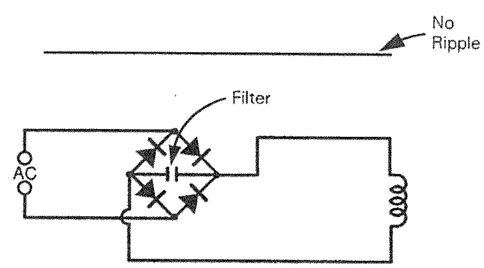


Fig. 4B - Rectified, filtered AC has little or no ripple present.

Relay Contact Life

Relay contacts are available in a variety of metals and alloys, sizes and styles. There is no such thing as a universal contact. The relay user should select contact materials, ratings, and styles to meet, as precisely as possible, the requirements of a particular application. Failure to do so can result in contact problems and even early contact failure.

For example, some contact materials require an arc to keep them free of sulfidation, oxidation, and contaminates. Such materials on contacts used in a dry or low-level circuit can result in the contacts failing electrically to close the circuit, even though they make physically. The contacts may look clean, but this is deceiving. In reality, there is a very thin film of insulating sulfidation, oxidation or contaminates on the surface of the contacts. This film must be removed for circuit continuity to be established, and arcing can accomplish this. (For dry and low-level circuits, bifurcated contacts should be used.)

Applications Considerations
In some applications, the contacts may be subjected to punishing current surges which can drastically reduce their life. Consider an incandescent lamp. A 40 watt, 120V AC lamp has a current rating of .33 ampere. The resistance of the filament when cold, however, is so low that initial inrush current may be as much as 6 amps! To attempt to switch the 40 watt lamp with, say 2 amp contacts will result in early contact failure.

The same situation exists in motor and transformer applications, and in applications where significant distributed line capacitance exists. During start-up, a motor can pull 600% or more of its running current. Thus, a 3 amp motor may actually pull 18 amps or more during start-up. A contact rated at least 20 amps should be used. Additionally, when disconnected, a motor acts as a voltage generator as it slows to a stop. Depending on the motor, it can feed back into the circuit voltages well in excess of rated line voltage. These voltages appearing across the separating contacts can cause a destructive arc to exist between the contacts, which can lead to early failure of the contacts. Because of this, it is desirable to suppress the arc. (Techniques for arc suppression are discussed later in this application note.)

Transformers can present an unusual trap for an unsuspecting relay user. When power is removed from a transformer, its core may contain remanent magnetism. If power is reapplied when voltage is of the same polarity as that of the remanent magnetism, the core may go into saturation during the first half-cycle of reapplied power. As a result, inductance will be minimal and an inrush current of perhaps 1,000% may exist for a few cycles until the core comes out of saturation. Worse, if reapplied power occurs at or near zero voltage and the increasing voltage aids remanent magnetism, the core **and** the air gap may saturate. An inrush of perhaps **4,000% or more** may result! Also, as with motor loads, when power is removed from a transformer, the transformer will develop a counter voltage which can cause a destructive arc to exist between separating contacts.

Distributed line capacitance presents particular problems for relays and their contacts. This occurs when a relay is located a considerable distance from the load to be switched. The instant the contacts close, distributed line capacitance charges before load current flows. This capacitance can appear as an initial short-circuit to the contacts, and can pull a current well in excess of load current. Prior to selecting a relay to switch a circuit when distributed line capacitance may be significant, instantaneous inrush current should be measured, and contacts selected accordingly.

Contact Materials

Fine Silver
Fine silver has the highest electrical and thermal properties of all metals. It is the best general purpose material available. However, it is affected by sulfidation. The rate of sulfidation indoors in a metropolitan area is approximately 70 micrograms per square centimeter per day. This sulfidation forms a film on the surface of the silver which increases contact interface resistance.

Because silver and silver alloys sulfidate, contact pressures must be great enough to break through this film. (Controlled arcing will also be helpful in that it burns off the sulfidation, and contact overtravel wipes away the residue.) While such pressures have no appreciable effect on silver-cadmium contacts, they do result in increased material wear of fine silver contacts. Also, an interface voltage of several tenths of a volt can result with fine silver contacts because of the sulfide film. This film has been known to capture and imbed airborne dirt. Breaking through this film generates electrical noise. Because of this, fine silver contacts are not used for low-level switching, such as audio circuits. Rather, fine silver and silver alloy contacts are for use in circuits of 12 volts, 0.4 ampere, or more.

Gold-Flashed Silver
For relays which must sit idle for long periods of time before initial operation, sulfidation of silver contacts can result in an impregnable contact interface resistance. Instead of specifying silver contacts for such applications, gold-flashed silver contacts should be specified. Gold flashing on each contact results in minimal sulfidation, and provides good electrical make upon contact. Because gold has a low boiling temperature, the flashing will burn off after just a few switch cycles if arc voltage and current is exceeded. The silver underlayment is then exposed, and may develop a sulfide film. Unless this situation can be tolerated, gold-flashed contacts should not be subjected to arcing.

Gold Overlay
A common contact for use in dry-and low-level circuits is gold overlay. The overlay is of sufficient thickness that it should not wear through to the base metal unless subjected to arcing conditions.

Silver Nickel
Depending on the application, material transfer may be quite prevalent with fine silver contacts. Typically, material tends to accumulate in the center of one contact, while the loss of material on the other contact leaves a hole, or "pit." This pitting may cause premature contact failure. In such an application, it may be desirable to use fine grain silver contacts. These contacts are alloyed with 0.15% nickel, which gives the contacts a fine grain structure. As a result, material transfer is evenly distributed across the entire surface of the contact and the contacts last longer.

Silver Cadmium Oxide
Silver cadmium oxide contacts have long been used for switching loads that produce a high energy arc. Silver cadmium oxide contacts are less electrically conductive than fine silver contacts, but have superior resistance to material transfer and material loss due to arcing. They do exhibit greater interface resistance between mated contacts, and also a slightly greater contact assembly heat rise. The minimum arc voltagerating of silver cadmium oxide is 10 volts and, like fine silver contacts, the silver in this alloy will oxidize and sulfidate. Therefore, an arc is necessary to keep these contacts clean.

SilverTin Indium Oxide
Silver tin indium oxide contacts, although not readily available, exhibit better resistance to arc erosion and welding than silver cadmium oxide contacts. They are even less electrically conductive, though, and are harder than silver cadmium oxide contacts. They have greater interface resistance between mating contacts and, therefore, a greater voltage drop and heat rise. At the present time, silver tin indium oxide is more expensive than silver cadmium oxide, and many relay users limit its use to applications such as incandescent lamp loads and capacitors where there is a massive inrush current during contact bounce. For low and medium power resistive and inductive loads, silver cadmium oxide is still the most commonly used and is recommended by Siemens Electromechanical Components (SEC). For applications where it is believed that silver tin indium oxide should be used, contact SEC applications engineering.

Silver Copper Nickel
Silver copper nickel contacts are for use in high inrush DC applications

such as incandescent lamps and capacitive loads. These contacts exhibit good resistance to welding.

Gold Silver Nickel Alloy

Gold silver nickel alloy contacts are for use in switching loads generally of less than one ampere, and are characterized by less electrical noise on make and break than fine silver contacts. Gold diffused silver contacts offer characteristics similar to gold silver nickel alloy, but are less expensive.

Palladium

Palladium contacts do not sulfidate or oxidize, and so offer extremely low electrical noise levels. They have an electrical life expectancy of approximately 10 times that of fine silver contacts. However, because of relatively poor conductivity properties, load currents are limited to about 5 amperes.

Palladium contacts require .006" to .012" overtravel to insure good wiping action. Because of this, they are used primarily on telephone-type relays—that is, relays on which the contact arms are parallel to the length of the coil, and on which such overtravel is easy to obtain. Also, palladium contacts should be bifurcated to help insure circuit continuity on contact closure.

Tungsten

Tungsten contacts are for use in high voltage applications, usually where highly repetitive switching is required. Tungsten has a melting temperature of 3,380°C which gives it excellent arc-erosion resistance.

Tungsten may develop troublesome oxide films, especially when used as the anode contact in some DC applications. Therefore, tungsten is often used as the cathode contact, and a palladium alloy used as the anode contact. Such a combination also minimizes contact interface resistance and material transfer.

Mercury

Mercury has a melting temperature of -38.87°C. Thus, as used in relays, it is in a liquid state. Mercury will cling to the surface of any clean metal, and is used as the contacts in mercury-wetted reed relays. It has good electrical conductivity and, being liquid, there is no material transfer build-up from contact to contact. Any such material transfer is negated by the fact that when the contacts open and the mercury returns to the pool in the bottom of the relay, fresh mercury takes its place at the very next switch operation. Mercury has a boiling temperature of 357°C. Because of this, mercury contacts cannot switch currents of more than a few amperes.

Contact Life

The electrical life expectancy of general purpose and power relays is generally rated to be 100,000 operations minimum, while mechanical life expectancy may be one million, 10, or even 100 million operations.

The reason electrical life is rated so low compared with mechanical life is because contact life is application dependent. The electrical rating applies to contacts switching their rated loads. When a set of contacts switches a load of less than rated value, contact life may be significantly greater. For example, 25 amp, 240V AC, 80% P.F. contacts may be expected to switch such a 25 amp load in excess of 100,000 operations. If these contacts are used to switch, say, a 5 amp, 120V AC resistive load, however, life may be in excess of a million operations.
Rated electrical life also takes into consideration arc destruction of the contacts. By use of appropriate arc suppression, contact life may be lengthened. Table 1 lists some arc voltage and current values for several different metals. An arc will ignite if both minimum arc voltage and current are exceeded. However, there will be no arc if load current at a given minimum arc voltage is less than the minimum arc current for that voltage. Likewise, there will be no arc if load voltage (or counter emf) is less than the minimum arc voltage of the contact metal.
As stated, an arc may be necessary in order to burn off the contacts any sulfidation, oxidation or contaminates. However, by its very nature, an arc is destructive. For maximum contact life, the arc should be suppressed as quickly as possible as soon as it ignites. Such arc suppression may be accomplished using techniques presented in this application note.

Table 1 -
Characteristics of Various Contact Materials

Material	Electrical Conductivity %IACS	Melt Voltage	Arc Voltage	Arc Current
Cadmium	24		10	0.5
Copper	100	0.43	13	0.43
Gold	77	0.43	15	0.38
Nickel	25	0.65	14	0.5
Palladium	16	0.57	15	0.5
Silver, fine	105	0.37	12	0.4
Tungsten	31	0.75	15	1.0

At voltage and current values of less than those required to ignite an arc, a spark may occur between separating contacts. This spark is a capacitive discharge, and is weak compared with an arc. Even so, the spark may be sufficient to keep sulfidation, oxidation, and contaminates from building up on the contacts. (Note: arc suppression has little, if any, effect on contact sparking.)

Contact life is terminated when the contacts stick or weld, or when excessive material is lost from one or both contacts and a good electrical make is not possible. These conditions are the result of cumulative material transfer during successive switching operations, and of material loss due to splattering.

Material Transfer and Material Loss

Material transfer occurs as a result of I^2R heat. As switch contacts begin to separate, the area of contact diminishes. Load current flowing through this increasingly constricted area generates heat which causes the contact material to melt, then boil. The liquified metal tends to collect on the cathode contact because that contact is cooler than the anode contact. Material transfer also occurs during arcing. However, under this condition, material transfer is from cathode to anode—the amount of transfer being dependent on the severity and duration of the arc, and the type of contact material used. Because contact material migrates first one way, then the other, the ideal arc suppression technique would be to quench the arc just as the anode recovers all of the material lost to the cathode just prior to the arc striking. However, this is impractical even to attempt.

Material **loss** is due primarily to splattering of the molten and boiling metal as contacts bounce on make. Such loss can be significant over the course of tens of thousands of operations, and the only practical way to minimize it is by arc suppression. Arc suppression quickly quenches the arc, thereby holding contact temperatures lower.

In DC applications, metal migration is predictable in that one contact is always negative, and the other, positive. In AC applications where switching is at random, either contact may be negative or positive when arcing occurs. Migration will not be in the same direction each time the switch opens, and material loss from either contact should not be significant—unless load conditions cause splattering.

Not all AC applications incorporate random switching, however. In some applications, the relay is operated at a set rate or frequency. In such instances, the contacts break load current at the same approximate point on the sine wave. That is, the same contact is always positive, and the other negative at the instant of contact separation. Material transfer during arcing will always be in the same direction. In such applications, contact arc suppression may be necessary.

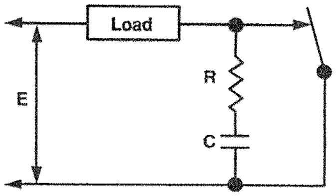
This is not to say that arc suppression is not needed on random-switching AC applications. On the contrary, arc suppression can help control the loss of contact material due to splattering of the molten metal. That is, when the arc is suppressed, contact temperature is held to a minimum.

Controlled arcing of short duration can be beneficial in actually achieving the rated life of the contacts. As stated, this is because such arcing burns off of the contacts any deposits that might prevent electrical make. Such control is achieved by arc suppression. Unless arcing and/or contact overtravel cleans the contacts, films may develop on the contact surfaces, or foreign matter may collect. For this reason, it is best to apply general purpose and power relays only in applications where load voltage (or counter emf) and current is in excess of the arc voltage and current ratings of those contacts.

Contact Protection

Perhaps the most popular method of quenching an arc between separating contacts is with an R-C network placed directly across the contacts. As the contacts just begin to separate and an arc ignites, load current feeding the arc will be shunted into the capacitor through the series resistance, depriving the arc of some of its energy. As a result, arc duration will be shortened and material loss will be minimized.

Contact Protection Diagram



Theoretically, the ideal arc suppression method would simply be a capacitor placed directly across the contacts. However, with no resistor in the circuit, when the contacts make, there is nothing to limit capacitordischarge current. This nearly instantaneous discharge current can generate a brief, but severe arc that may cause welded contacts, depending on contact material and characteristics. Thus, the resistor is necessary to limit capacitor discharge current. However, there is one drawback. That is, the resistor tends to isolate the capacitor from the very contacts the capacitor is supposed to protect. Because of this, the amount of resistance should be kept as small as possible.

Many relay users are unfamiliar with the selection of a capacitor for arc quenching service. To begin with, AC differs from DC in that AC crosses zero 120 times per second for 60 Hertz service while DC, of course, is continuous current. In AC service, the capacitor need not be as large as in DC service because the AC arc will extinguish at a zero crossover point. In DC service, the capacitor must continue to shunt load current sway from the contacts until the contacts separate far enough apart for the arc to extinguish.

Capacitor Selection

Assume a DC application of 28 volts, 5 amperes. Further assume an R-C network is needed that will result in contact voltage of perhaps 15 volts 1 μsec. after the contacts have separated. Since the value of resistance should be as small as possible, a 2 ohm resistor might be chosen. At 2 ohms, peak capacitor discharge current will be 14 amperes at time zero. Depending on contact material and size, this 14 amperes may be quite acceptable for such a short period of time.

Conact voltage—that is, arc voltage—at any given instant of time is simply the sum of the voltage drop of the resistor and the capacitor voltage. Select a capacitor voltage of, say, 10 volts. The remaining 18 volts must appear across the 5.6 ohm load and the 2 ohm resistor. Thus, instantaneous capacitor current is:

$$I = \frac{E}{R} = \frac{18V}{7.6\Omega} = 2.4 \text{ ampere,}$$

and the voltage drop of the 2 ohm resistor is 4.8 volts. Arc voltage, therefore, one microsecond after contact separation is 4.8V + 10V = 14.8V, or about 53% of supply voltage.

To determine the size of capacitance needed, the basic equation for capacitor voltage may be used:

$$e_c = E(1 - \varepsilon^{-t/RC})$$

Rearranging the equation to solve for capacitance gives 1.1 μfd.

$$c = \frac{-t}{[l_n(1-\frac{e_c}{E})]R} = 1.1 \times 10^{-6} \text{ farad}$$

Where: $t = 1\ \mu$sec.
e_c = 10 volts = capacitor voltage at time t.
E = 28 volts (for AC, use peak value).
R = 2.0 ohms.

The next question concerns capacitor construction. Can the capacitor withstand discharge surge currents? When the contacts close, the capacitor will discharge through the resistor. For a 1 μfd. capacitor and a 2 ohm resistance, the time constant is: R x C = 2 x 1 μfd. = 2.0 μsec.

To determine discharge di/dt:

$$i = C\frac{dv}{dt} = 1 \times 10^{-6}\,\frac{28 \times .63}{2.0 \times 10^{-6}} = 8.8A_{avg}/\mu\text{sec.}$$

where; .63 is the capacitor voltage loss during one time constant of 2.0 μsec.

This di/dt isn't very severe and a wide variety of capacitors should be able to withstand it. However, the di/dt of a 5 ampere 240 volt AC application would be 107A/ μsec. at peak of the AC line—that is, 340 volts; and capacitor selection* should be made accordingly.

Of course, di/dt may be lowered by a larger value of resistance to limit capacitor discharge current even more. But, the greater the value of resistance, the less effect the capacitor has on the arc.

Other Arc Suppression Methods

For quenching DC arcs in certain applications, relays are available that have a permanent magnet located in close proximity to the contacts. The magnet repels the DC arc, thereby stretching the arc and causing it to extinguish quickly.

Some relay users connect a diode across the inductive load to prevent countervoltage from reaching the contacts. When the relay contacts open, the storedenergy of the inductance recirculates through the diode, not through the arc. While this is an acceptable method of protecting the contacts, it does result in lengthened hold-up time of the inductive load. For those applications that cannot tolerate lengthened hold-up time, a resistor may be placed in series with the diode. The resistor does, however, lessen the effectiveness of the diode and, usually, a compromise must be reached by trial and error.

By using a zener diode in place of the resistor, hold-up time is greatly reduced. This is because the diodes cannot turn on until the voltage across them equals the sum of their voltage drops.

In some circuits, space is at a premium and there may not be sufficient room for a zener and a regular diode. In such circuits, some designers use a metal oxide varistor. The MOV performs in a manner similar to back-to-back zener diodes. And, since the MOV is a bidirectional device, it can be used in both AC and DC circuits.

An added benefit of arc suppression is the minimization of EMI. An unsuppressed arc between contacts is an excellent noise generator. Such noise can be troublesome to sensitive components in a circuit, or within the RFI field. In worst-case conditions, EMI can cause unwanted turn-on of IC logic gates, SCRs, and triacs, and can cause damage to other semiconductor devices.

*Suggested capacitor atypes are metalized foil and film foil. Check capacitor specifications for dv/dt and di/dt ratings.

Application Notes

- Measure the current inrush of the circuit to be switched before specifying the relay.
- Never parallel relay contacts to double the contact rating. Unless the relays are specially adjusted, they will not pick up and drop out simultaneously. Even if they were to be specially adjusted, they would not hold this adjustment over life.
- Paralleling Form C contacts may result in an unwanted make-before-break arrangement.
- Contacts rated low level to 2 amps may be used to switch a 2 amp load. Once having done so, however, they cannot be used to switch reliably a low level load.
- In a circuit comprising a series of open relay contacts (AND logic), all but the last set of contacts to close will be dry. Likewise, in a circuit comprising a series of closed contacts, all but the first to open will be dry.
- The use of many relay contacts in series may be limited by total circuit contact resistance.
- A "low level" circuit that pulls a capacitive inrush current or develops an inductive counter emf is not low level. Worst case circuit conditions dictate contact rating, not steady state conditions.

Temperature Considerations for DC Relays

Relays and temperature are intertwined. When a relay is exposed to various temperatures, its operating characteristics change dependent upon the temperature. The most notable changes occur in the pick-up voltage (V_{PI}) and coil resistance (R_C). The coil winding of a relay is produced with copper wire and thus the coil resistance varies with the temperature coefficient of copper. For the temperature range that a relay will normally be exposed to, the change in copper follows the form of:

Eqn. 1

$$R_1 = R_0 \times (1 + A \times (T_1 - T_0))$$

where:

- R_1 = Resistance at temperature T_1
- R_0 = Resistance at temperature T_0
- A = Slope of a line from a point (- 234.5,0) through the point (T_0, 1)(A = 0.003929 at T_0 = 20°C)
- T_1 = New temperature of interest
- T_0 = Reference temperature (20°C is typically used for this value)

Now that we can calculate the coil resistance at a new temperature given a value at some known reference temperature, let us look at the pick-up voltage. For a DC relay, the magnetic force developed is proportional to the Ampere-turns developed in the coil. Since the mechanical forces are fairly constant over the normal temperature range (and the number of turns is fixed), we can also deduce that the pick-up current (I_{PI}) will be constant. If pick-up current is constant and coil resistance varies, it follows that pick-up voltage ($V_{PI} = I_{PI} \times R_C$) varies directly as the coil resistance. This leads to a simple mathematical method to determine coil resistance and pick-up voltage at any temperature if a reference point is known.

For example:

Assume that a relay has the following parameters at 20°C (T_0).

R_C = 90 Ohms

V_{PI} = 6.5 volts

Calculate the new coil resistance at 105°C (T_1)

From Eqn. 1 we find:

$$R_1 = 90\Omega \times (1 + 0.003929/°C \times (105°C - 20°C))$$
$$= 90\Omega \times (1.334)$$
$$= 120.1\Omega$$

Eqn. 2

To find the new pick-up voltage, we replace R_1 and R_0 with V_1 and V_0 respectfully to find:

$$V_1 = 6.5 \text{ volts} \times (1.334)$$
$$= 8.67 \text{ volts}$$

To find the factor, A, the following equation is provided:

$$A = 1 / (T_0 + 234.5)$$

For three common reference temperatures, A is as follows:

European & Asian at 20°C:	A	=	0.003929
International (IEEE) at 23°C:	A	=	0.003883
United States at 25°C:	A	=	0.003854

It is not a critical matter which reference temperature is used. The international was selected as 23°C (± 3°C) to encompass both of the previous standards and thus appease everyone. It is recommended that this value be used whenever specifying new products since it is not more than 1.2% from either the 20 or 25°C reference and will provide future consistency if adopting ISO countries begin to utilize it. The equivalent values can be calculated from this reference for the others. Not that almost all European specifications still use the 20°C reference while many U.S. firms are beginning to utilize the 23°C reference.

While temperature changes affect relay parameters, the power dissipated within the relay also affects the temperature in most applications. The power dissipated within the relay may be broken down into two major components. The first is heat generated in the relay coil when voltage is applied to it. This heat creates a temperature rise (or increase) in the relay coil and package. The amount of temperature rise created is dependent upon several factors such as the volume of copper wire used, insulation thickness, insulation type, bobbin material, bobbin thickness, terminal size, conductor size, and several other factors that are design related. Each of these factors will either enhance or resist the flow of generated heat out of the coil assembly and into the ambient air. For a given relay design, these factors can be summed together into a value called the "coil to ambient thermal resistance" of the relay. The dimensions of such a value are °C/Watt. The thermal resistance is analogous to the electrical resistance and the temperature rise created by coil power dissipation follows the equation:

Eqn. 3

$$T_{RC} = \theta_{CA} \times P_D$$

where:

- T_{RC} = Temperature rise caused by coil dissipation
- θ_{CA} = Thermal resistance from coil to ambient
- P_D = Final steady-state power dissipated in coil

For normal relay temperature ranges, this relationship is nearly linear and consistent under the following conditions:

1. The relay is in still air and not subjected to significant air flow or the value of θ_{CA} was determined with an air flow identical to the end application (difficult to simulate). For pc board relays, the still air assumption is often valid because of the end product enclosure.
2. All power calculations deal with the coil resistance at the final coil temperature (T_C) attained. If only room temperature coil resistance were used, the resulting non-linearity would result in significant errors at higher temperatures.
3. The value for thermal resistance is determined from test data where the relay carried no load current.

We now have the information necessary to calculate the final coil temperature from data book parameters under no load conditions for a relay. Let us try an example.

Given the following:

T_0 = 20°C

V_0 = V_{PI} = 6.8 volts

R_0 = 90 Ohms

V_A = 13.5 volts (V_A = applied coil voltage)

θ_{CA} = 40°C/W

T_A = 85°C (T_A = ambient temperature)

I_L = 0 Amperes (I_L = load current)

Determine the following:

1. "Cold start" pick-up voltage (with the coil previously unenergized) and coil resistance at T_A
2. Final steady-state coil temperature (T_C) and resistance for V_A
3. "Hot start" pick-up voltage (after coil energized at V_A) at T_A and V_A

First we solve Eqn. 1 for R_1 at 85°C

$$\begin{aligned} R_1 &= 90 \times (1 + 0.003929 \times (85 - 20)) \\ &= 90 \times (1.2554) \\ &= 113.0 \text{ Ohms} \end{aligned}$$

Again we find V_1 at 85°C by using the same factor

$$\begin{aligned} V_1 &= 6.8 \times (1.2554) \\ &= 8.54 \text{ volts} \end{aligned}$$

Now the difficult part, finding T_C with 13.5 volts applied to the coil.

From Eqn. 3, and realizing that $T_C = T_A + T_{RC}$ and $P_D = V_A{}^2/R_C$:

Eqn. 4

$$T_C = \theta_{CA} \times V_A{}^2/R_C = T_A$$

Now we have a problem. As we have already seen, R_C changes with temperature. Since we are calculating temperature, we have two variables. The easiest approach to use here is simple iteration. Let us start by using the initial coil resistance at the ambient temperature of interest:

$$\begin{aligned} T_{C1} &= (40 \times ((13.5)^2 / 113)) + 85 \\ &= 64.5 + 85 \\ &= 149.4°C \end{aligned}$$

We must now calculate a new value of R_C using T_{C1} and Eqn. 1.

$$\begin{aligned} R_{C1} &= 90 \times (1 + 0.003929 \times (149.5 - 20)) \\ &= 90 \times (1.5088) \\ &= 135.8 \text{ Ohms} \end{aligned}$$

Now using Eqn. 4 again;

$$\begin{aligned} T_{C2} &= (40 \times ((13.5)^2 / 135.8)) + 85 \\ &= 53.7 + 85 \\ &= 138.7°C \end{aligned}$$

Again we would calculate a new value of R_C at T_{C2} and repeat the process until a suffient accuracy is obtained. With several iterations, the answer to this example becomes:

$$T_C = 140°C$$

Now that we have the final coil temperature, we can find the coil resistance with Eqn. 1.

$$\begin{aligned} R_C &= 90 \times (1 + 0.003929 \times (140 - 20)) \\ &= 90 \times (1.4715) \\ &= 132.4 \text{ Ohms} \end{aligned}$$

The "hot start" pick-up voltage is found using the same factor:

$$\begin{aligned} V_1 &= 6.8 \times (1.4715) \\ &= 10.0 \text{ volts} \end{aligned}$$

The only remaining piece to the puzzle is how a contact load current affects the temperature of the relay coil and thus its parameters. Past studies imply that the contact power dissipation may be treated as a separate heat source that adds heat into the relay package. Its effect on coil temperature is dependent upon many factors including package size, contact to coil distance, contact terminal size, connecting wire size, shared thermal paths, etc. Again, these factors can be lumped into a contact to coil thermal resistance. This leads to an equation similar to Eqn. 3.

Eqn. 5

$$T_{RL} = \theta_{CC} \times P_K = \theta_{CC} \times R_K I_L{}^2$$

where:

T_{RL} = Temperature rise in coil caused by the load current

θ_{CC} = Thermal resistance from contact to coil

P_K = Power dissipated in contacts

R_K = Contact circuit resistance

I_L = Load current flowing through the contact circuit

As an alternative possibility, and in an effort to provide a best fit curve to earlier test data, the following equation has yielded good approximations.

Eqn. 6

$$T_{RL} = K_{RL} \times I_L{}^{1.85}$$

This formula has been empirically derived from several test results and has successfully predicted final coil temperature rise caused by contact loads. The value K_{RL} can be derived from a two step temperature test. First determine temperature rise with no contact load and then measure under the same conditions with a contact load. The coil temperature rise minus the part caused by the coil power dissipation yields a T_{RL} and I_L combination that may be used to solve Eqn. 6 for K_{RL}.

The final coil temperature is then found by adding the respective components to obtain:

Eqn. 7

$$\begin{aligned} T_C &= T_A + T_{RC} + T_{RL} \\ &= T_A + \theta_{CA} \times (V_A{}^2 / R_C) + K_{RL} \times I_L{}^{1.85} \end{aligned}$$

This formula also requires solution by iteration. Since the only difference here is the added T_{RL} term, the following example is left to the reader.

All conditions the same as in the previous example except with:

$$\begin{aligned} I_L &= 20 \text{ Amperes} \\ K_{RL} &= 0.029 \end{aligned}$$

The answers should be 113.0 Ohms, 8.54 volts, T_C = 146.5°C, R_1 = 134.73 Ohms, and V_1 = 10.18 volts.

The reader should now be able to determine the steady-state characteristics for any temperature and voltage combination given the appropriate relay data. It must be stressed that the values obtained here apply to DC relays operated continuously at these values. Intermittent duty (with short, i.e. less than 1 minute, "on" times and longer "off" times) may result in substantially lower temperatures. Therefore if a specific known duty cycle is given for the relay operation, testing at these conditions could yield acceptable results for final coil temperature when the continuous duty temperatures calculated here would not. The methods discussed here are applicable to standard DC relays and while the coil resistance formula will work for Polarized DC relays (one that utilizes a permanent magnet) and AC relays as well, the pick-up voltage equations will not work in such cases. With a polarized DC relay the temperature induced change in magnetic force of the magnet must be considered. This is normally such that it reverses part of the change in pick-up voltage caused by the copper wire resistance. In the case of AC relays, the inductance contributes a significant portion of the coil impedance and is related to the turns in the coil. since the inductance varies only slightly with temperature, the pick-up voltage exhibits less variation over temperature than for DC relays.