

Measuring and Improving DC Control Circuits

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Presented at the
Beijing Electric Power International Conference on Transmission and Distribution
Beijing, China
October 18–21, 1999

Previously presented at the
53rd Annual Georgia Tech Protective Relaying Conference, May 1999,
and 52nd Annual Conference for Protective Relay Engineers, March 1999

Originally presented at the
25th Annual Western Protective Relay Conference, October 1998

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INTRODUCTION

A protection system consists of circuit breaker(s), instrument transformers, protective relay(s), and a dc system. Every component of this system must perform properly for the system to work reliably. This paper concentrates on measuring and improving the health of the dc portion of the protection system.

The dc system consists of several parts:

- a power source including the battery and charger;
- wiring and connections;
- dc system protection;
- switches, including protective relay contact outputs, auxiliary relay contacts, breaker auxiliary contacts, and isolation switches; and
- loads, including protective relay contact inputs, auxiliary relay control coils, and circuit breaker trip and close coils.

We discuss a battery voltage monitor circuit suitable for inclusion in a protective relay. This circuit helps detect and locate inadvertent dc grounds. In addition, this circuit helps improve the security and reliability of the relay contact inputs.

Inadvertent dc grounds can falsely assert contact inputs and operate auxiliary coils. In extreme cases, these grounds can even operate circuit breaker trip and close coils. We review a method to decrease the impact of dc grounds on these circuits.

We discuss the benefits of a contact input circuit that goes beyond the traditional role of detecting contact or switch closure; it actually measures the applied dc voltage.

We review how small metallic contacts interrupt dc current. Further, we discuss the benefits of a protective relay contact output with near instantaneous make-times and the capability to interrupt circuit breaker trip and close current.

BATTERY VOLTAGE MONITORING AND DC GROUND DETECTION

Figure 1 shows a small portion of a typical dc system. The batteries usually are series strings of lead-acid cells. While we discuss 125 Vdc nominal battery systems, the following discussion applies equally well to other voltages.

Resistors R1 and R2 are replaced sometimes by lamps. The common connection of R1 and R2 is grounded. This references the battery to ground while still providing some isolation from ground. Isolation from ground is important, given that inadvertent shorts from the dc system wiring to ground do occur and the system must remain operative.

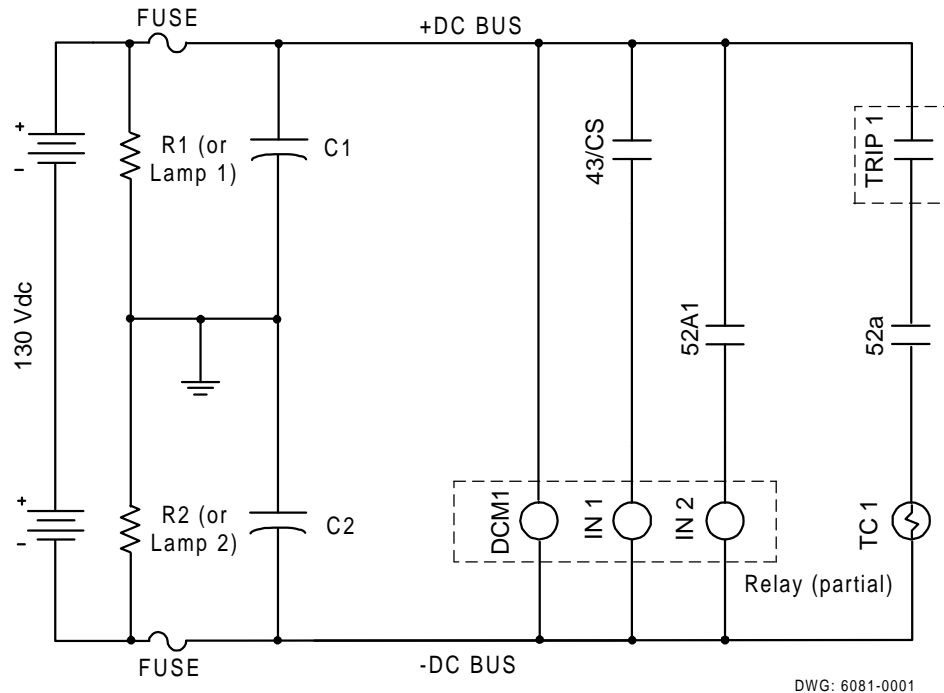


Figure 1. Portion of a Typical DC System

where:

- | | | |
|-------------|---|---|
| C1 and C2 | ≡ | Capacitance Due to Wiring, Surge Protection, Power Supplies, etc. |
| R1 and R2 | ≡ | Battery Ground Centering Resistors |
| 43/CS | ≡ | Panel Mounted Feature Control Switch |
| TRIP1 | ≡ | Protective Relay Trip Output |
| 52A1 | ≡ | Breaker Auxiliary Contact |
| IN1 and IN2 | ≡ | Protective Relay Contact Input |
| DCM1 | ≡ | DC Monitor |
| FUSE | ≡ | Relay Panel Fuse |
| TC 1 | ≡ | Trip Coil 1 |
| 52a | ≡ | Breaker Auxiliary |

For example, consider an inadvertent short-circuit from the +DC bus to ground. Before the inadvertent ground occurs, the current flowing through R1 and R2 is equal. Thus, under normal operation, R1 and R2 each support a voltage equal to half the total battery voltage. The inadvertent ground shorts out resistor R1. Therefore, the +DC bus drops to ground potential, and the -DC bus drops to the full battery voltage below ground potential. If Lamps 1 and 2 replace R1 and R2, respectively, Lamp 1 extinguishes during the positive dc ground, and Lamp 2 glows brighter. Thus, the lamps detect and help locate the dc ground. However, lamps cannot notify remote personnel of a dc ground.

A single dc ground is not destructive. If a second short circuit is applied from the -DC bus to ground, the dc protection system (panel fuses in Figure 1) operates to isolate the fault. It is important to isolate and remove dc grounds before this happens. Unfortunately, the method most often used to isolate dc grounds involves removing panel fuses or opening panel circuit breakers.

Figure 2 shows a dc ground detection and battery monitor circuit suitable for use in a protective relay (shown as DCM1 in Figure 1). The circuit connects to the +DC and -DC busses, and to ground. These connections are already present in the protective relay in the form of power supply connections and a surge ground connection. The circuit measures the voltage between the +DC bus and ground and between the +DC and -DC busses. Resistors R3 and R6 are a very high value (22 MΩ) and are rated for high voltage (3 kV). For a 125 Vdc battery, they represent no more than a 3μ A leakage path from the +DC and -DC busses to ground.

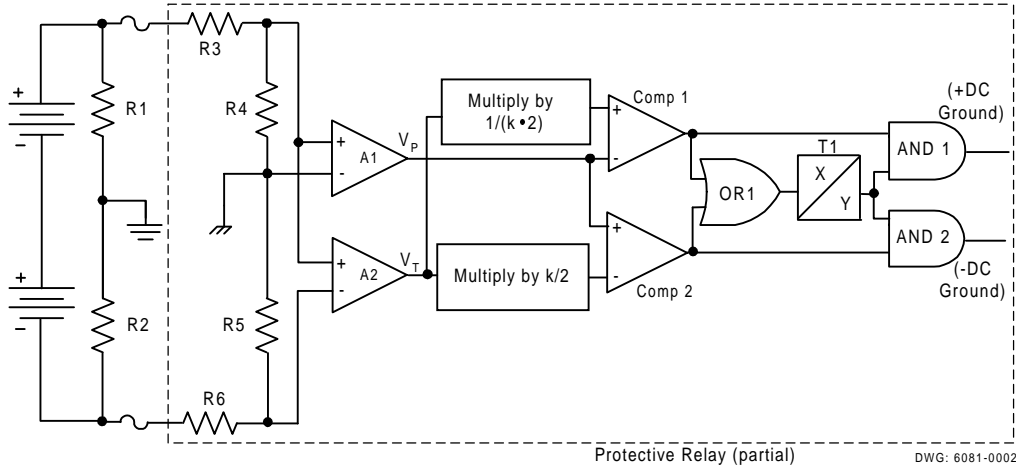


Figure 2. Battery Voltage Monitor and DC Ground Detector

The two instrumentation amplifiers (A1 and A2) sense the current flowing through R3 and R6 (via the voltage across R4 and R4 + R5, respectively). A1 produces a voltage, V_P , which is proportional to the voltage from the +DC bus to ground. A2 produces a voltage, V_T , that is proportional to the total voltage from the +DC bus to the -DC bus. The value $V_T - V_P$ is proportional to the voltage from the -DC bus to ground.

We use the values V_T and V_P to detect and help locate inadvertent grounds in the dc control wiring. We want to avoid any nuisance alarms. Nominally, V_P is approximately equal to $\frac{1}{2} \cdot V_T$. When $V_P > \frac{1}{2} \cdot V_T$, current is being shunted from the -DC bus to ground. If $V_P < \frac{1}{2} \cdot V_T$, current is being shunted from the +DC bus to ground.

To avoid nuisance alarms, we create a dead band (see also Figure 3)

$$\frac{V_T}{2 \cdot k} \leq V_P \leq \frac{k \cdot V_T}{2}; \text{ where } 1 \leq k \leq 2$$

When V_P is within this band, the dc system is in nominal operation and no alarm occurs. If $V_P \geq (k \cdot V_T)/2$, the relay alarms for a negative dc ground. The relay alarms for a positive dc ground when $V_P \leq V_T/(2 \cdot k)$. Parameter k determines the sensitivity of the alarm conditions. Consider a value of 1.03 for k , which causes an alarm for $0.485 \cdot V_T \leq V_P \leq 0.515 \cdot V_T$. If the battery voltage $V_T = 130$ Vdc, then the relay alarms for 63.1 Vdc $\leq V_P \leq 66.95$ Vdc.

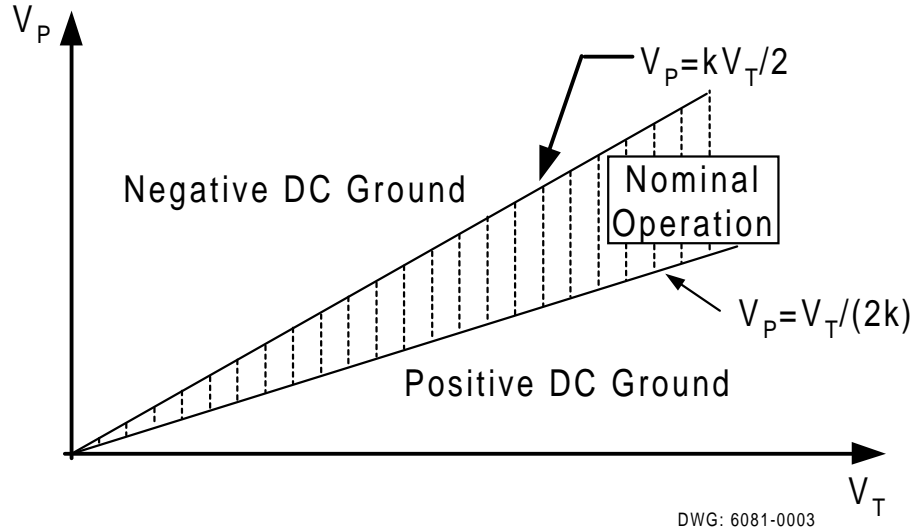


Figure 3. Alarm and Nominal Operation Regions for Circuit in Figure 2

Figure 2 also shows the logic for implementing the dead band detector described above. The output of comparator COMP1 asserts if $V_P \leq V_T/(k \cdot 2)$. The output of comparator COMP2 asserts if $V_P \geq (k \cdot V_T)/2$. If either comparator output asserts for at least time X, the output of timer T1 asserts and the relay alarms for a dc ground.

THE EFFECTS OF DC GROUNDS

One major West Coast utility reports measuring 100 - 400 μF of capacitance connected from ground to the +DC and -DC busses in its larger substations. This capacitance comes from dc surge capacitors in electronic equipment plus normal wiring capacitance. These capacitors store enough energy to energize some loads immediately following dc grounds. C1 and C2 in Figure 4 represent that capacitance. For our examples, we use the 300 μF value to illustrate a severe condition. Consider the effects of dc grounds applied at the points labeled 1 through 4 in Figure 4.

Case 1. +DC Bus Ground

An inadvertent ground on the +DC bus shorts out R1. No equipment is affected for this circuit: the trip coil and relay inputs do not have a differential voltage across their terminals and the discharge/charge paths for C1/C2, respectively, are not through any of the dc equipment shown.

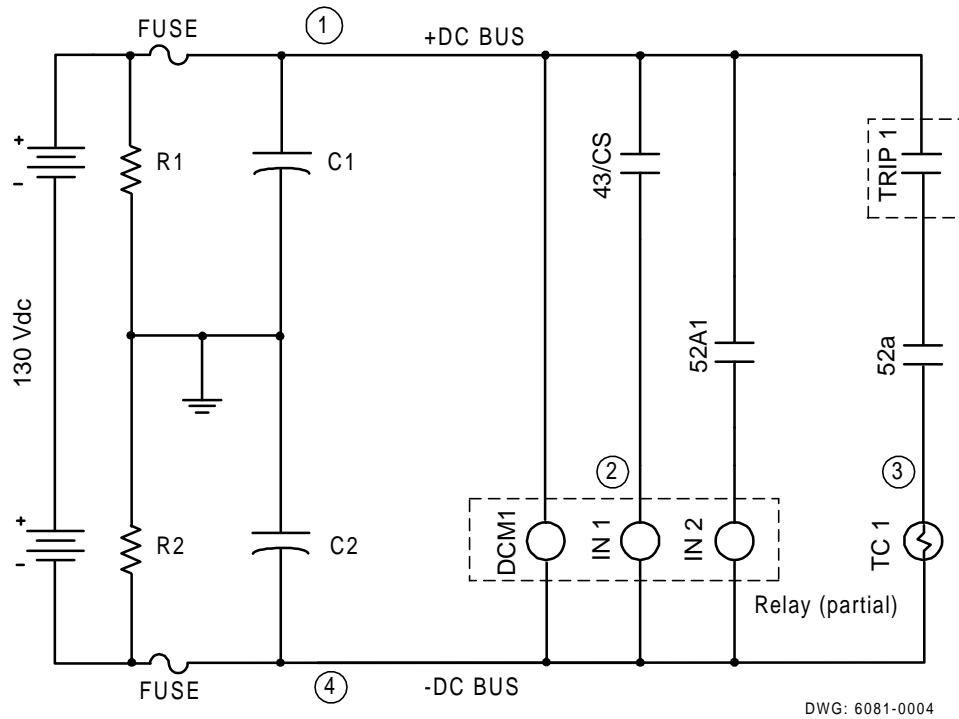


Figure 4. A Portion of a DC System

Case 2. Ground Between the Open 43/CS Contact and IN1

Assume contact input IN1 has resistance much greater than R1 and R2. Typical values for R1 and R2 might be 3.3 kΩ. A typical value for the resistance of IN1 might be 30 kΩ. In this case, an inadvertent ground between the open 43/CS contacts and the relay input IN1 applies nearly half the total battery voltage to IN1 (see Figure 5). If IN1 asserts at less than half the battery voltage, a misoperation may occur.

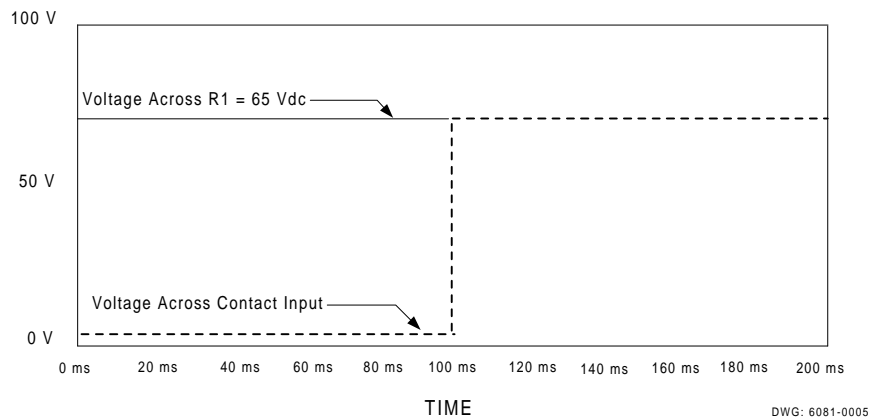


Figure 5. Contact Inputs Assert During a DC Ground if Pickup $< 1/2 \cdot V_{BATT}$

Case 3. Ground Between the Trip Contact and the Trip Coil

An inadvertent ground between the trip contact and the trip coil places the trip coil in parallel with R2 and C2. The trip coil resistance typically is much less than the value of R2. This causes the voltage across R2 and C2 to decrease and the voltage across R1 and C1 to increase for this dc ground. When the voltage across a capacitor changes, it discharges or charges. In this case, C2 discharges and C1 charges through the trip coil. The charge and discharge currents add constructively to nearly half the nominal trip current. Because both capacitors contribute to the problem, they appear in parallel. The time constant for the circuit is the product of the trip coil resistance and (C1 + C2). Assuming C1 = C2 = 300 μ F, and a trip coil resistance of 13 Ω (10 A nominal), this trip coil is energized with a 4 A peak, 13 Ω • 600 μ F = 8 ms time-constant current spike (see Figure 6). This may be enough to operate the trip coil and trip the circuit breaker.

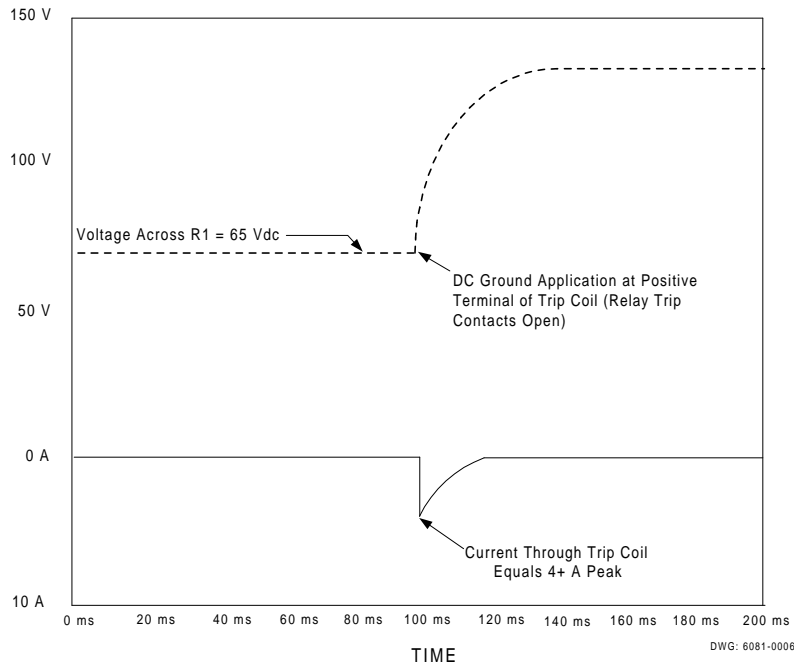


Figure 6. DC Ground at Trip Coil Input Terminals Operates Sensitive Trip Coils

Case 4. -DC Bus Ground

An inadvertent ground on the -DC bus shorts out R2. No equipment is affected for the circuit shown: the trip coil and relay inputs do not have a differential voltage across their terminals, and the charge/discharge path for C1/C2, respectively, are not through any of the dc equipment shown.

Cases 3 and 4 show that, when considering dc grounds on the positive terminals of loads, we usually have one of two cases:

- If the load resistance is an order of magnitude greater than the battery centering resistors, then a dc ground places up to half the battery voltage across the load indefinitely.

- If the load resistance is less than the battery centering resistors, then all of the surge capacitors connected to either dc bus charge/discharge through the load. The dc ground momentarily places up to half the battery voltage across the load.

SURGE CAPACITORS ON LOADS OR CONTACTS

In the cases we considered above, grounds on the +DC and -DC busses had little or no effect on the dc equipment. However, if we add surge capacitance to either the contact input IN1 or to the control switch 43/CS, the situation changes. Figure 7 shows such surge capacitance (C3).

Reconsider Case 1, where we applied a dc ground to the +DC bus. Before this dc ground, C3 is charged to -65 V. After the dc ground, C3 charges to -130 V. Thus, C3 discharged an additional 65 V due to the dc ground on the +DC bus. Switch 43/CS is open, so the discharge current must pass through IN1. The voltage appearing across IN1 is limited to half the battery voltage. If IN1 only asserts for voltages greater than half the battery voltage, then it cannot assert falsely for this dc ground. (A similar situation exists for a negative dc ground.)

What if IN1 is allowed to assert for input voltages as low as one-fourth of the battery voltage? The circuit time constant is the product of the IN1 resistance and the surge capacitance. A typical surge capacitor on a contact input or output is 470 pF. A typical resistance for a 125 V contact input is 30 kΩ. The time constant of this circuit is then 14.1 μ seconds (s). For the +DC ground, the contact input voltage is greater than the minimum assertion voltage (one-fourth of the total battery voltage) for about 60% of a time constant, or about 9 μs. If a protective relay reads IN1 16 times per power system cycle or once every 1.04 ms, we would expect one false assertion of IN1 for every $(1.04 \text{ ms}/(9 \mu\text{s})) = 116$ dc grounds. This probability may be unacceptable but is easily remedied by time-qualifying IN1 for two or more samples. A better solution might be to remove the surge capacitor. We believe that surge capacitors are unnecessary for properly designed contact inputs or outputs.

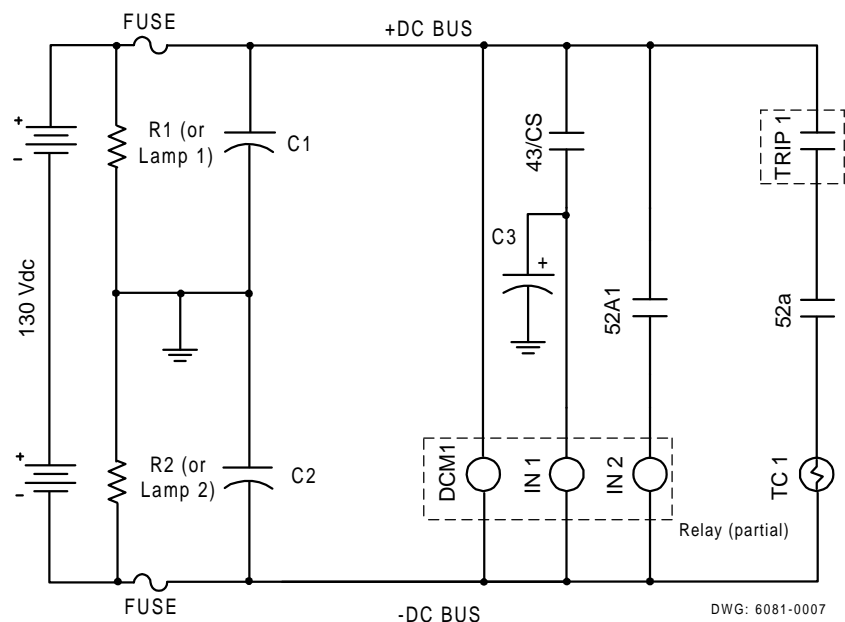


Figure 7. DC Control Circuit With Surge Capacitance

NEGATIVE-GROUNDED DC SYSTEMS

The discussion above shows that dc grounds between contacts and loads place up to half the battery voltage on the load. If the contact or load has significant surge capacitance, then a dc ground on either dc bus can momentarily place up to half the battery voltage on the load. If the load is a contact input, we can solve these problems by ensuring the input does not assert for less than half the battery voltage or by time-qualifying the input. If the load is an auxiliary relay coil, or a circuit breaker trip or close coil, those solutions may be impractical. The case of a dc ground between a trip (close) contact and the trip (close) coil is particularly troublesome, because all surge capacitors or stray wiring capacitance connected to either dc bus charge or discharge through the coil.

Figure 8 shows a system that is less susceptible to the effects of dc grounds between trip (close) contacts and trip (close) coils. For this system to be effective, R3 must connect to the same dc bus as the trip/close coils. Switch SW2 is closed under normal operating conditions. We choose R3 to be much less than R1 or R2, but large enough that a dc ground on the bus opposite SW2 does not produce large currents when SW2 is closed. Assume R3 is 100 Ω . This value of R3 limits the current produced by a ground on the positive dc bus when SW2 is closed to less than 1.5 A.

Because R3 is a much lower impedance than R2, the negative dc bus and the positive terminal of trip or close coils are less than 5 V below ground potential with SW2 closed. A dc ground at the positive terminal of the coil creates less than 5 V across that coil, regardless of the coil resistance.

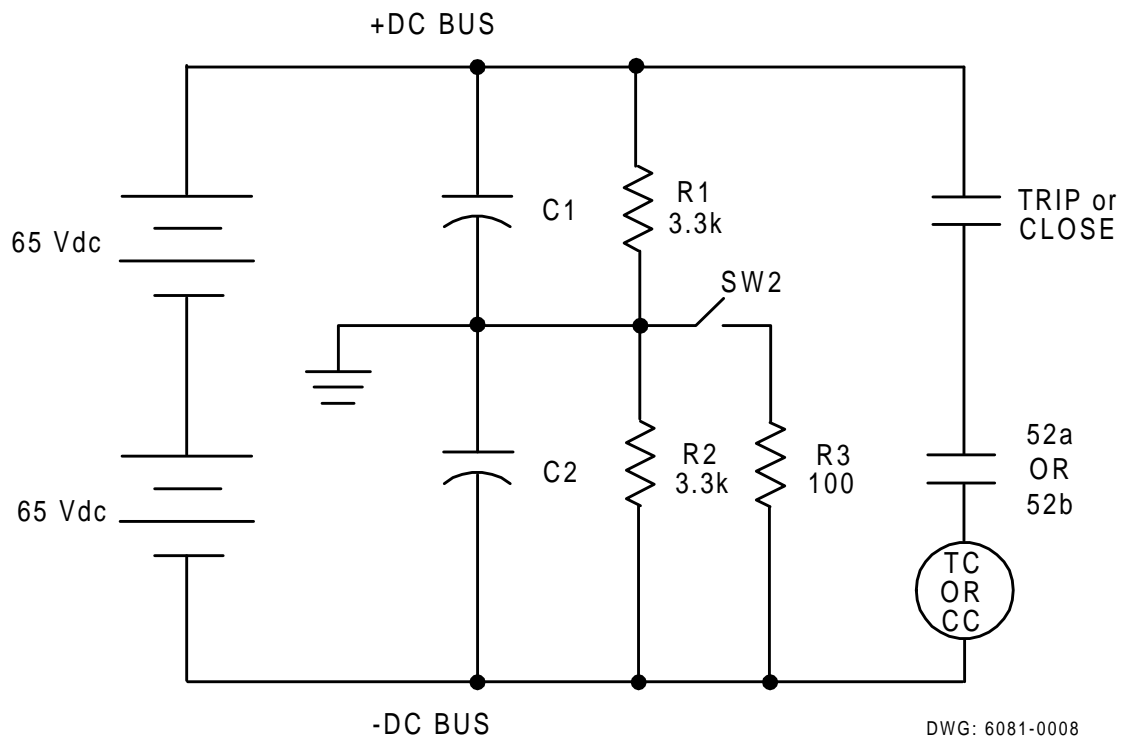


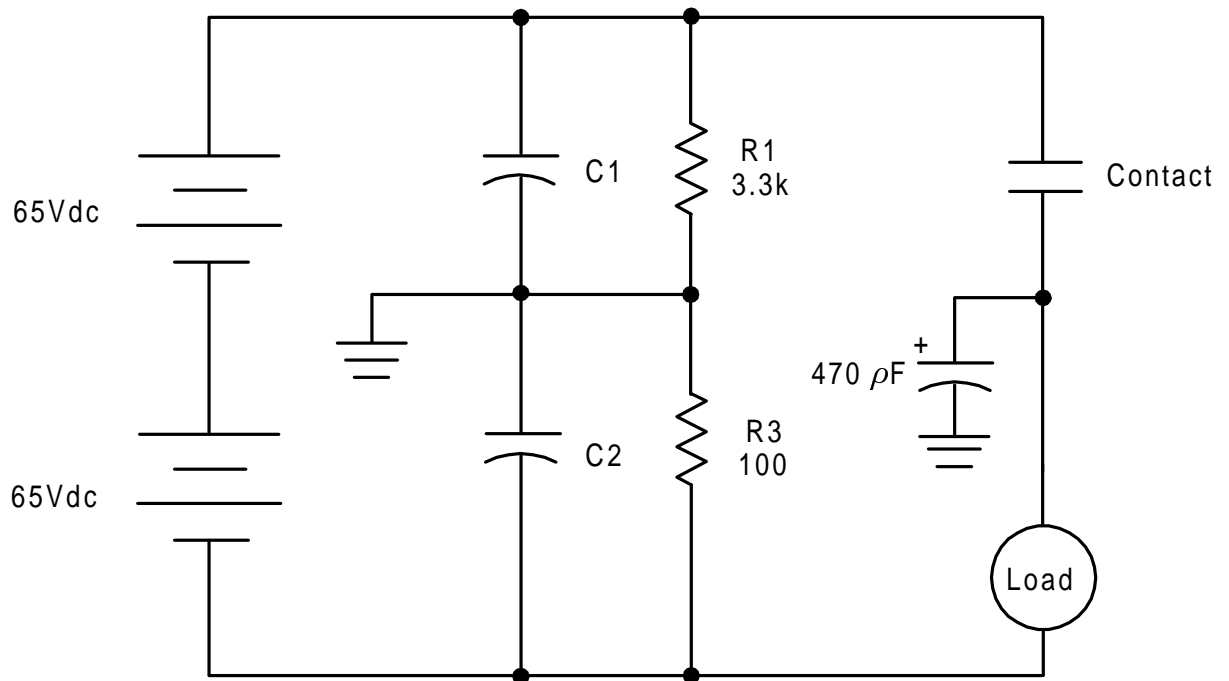
Figure 8. A System to Lessen Impact of DC Grounds on Trip and Close Circuits

One disadvantage of the circuit shown in Figure 8 is that it prevents detection of -DC bus grounds while SW2 is closed. One major utility using this scheme opens SW2 routinely to check for -DC bus grounds. In applications at this utility, SW2 is a manually controlled switch. In manned substations, an operator opens SW2 daily. In unmanned installations, operators open SW2 whenever they patrol the substation.

Control of SW2 can be automated. In a relay equipped with the dc ground detection logic shown in Figure 2, the relay would open SW2 momentarily and check for dc grounds.

Switching SW2 is the same as applying and removing a negative dc ground. As discussed above, when contacts or contact inputs have significant surge capacitance, a dc ground on either dc bus can momentarily place up to half the battery voltage on the contact input. The situation is actually worse when SW2 is closed.

Consider Figure 9, which shows a contact output connected to a contact input with switch SW2 closed. Either the contact output or the contact input has $470 \mu\text{F}$ of surge capacitance. Assume we place a ground on the +DC bus in Figure 9 with SW2 closed. Before application of the positive dc ground, the surge capacitor is charged to approximately -5 V . After the dc ground, the surge capacitor is charged to -130 V . This means that the surge capacitor discharged 125 V . Because the contact output is open, this discharge current must pass through the contact input. In fact, the dc ground places almost full battery voltage momentarily across the contact input. Therefore, all contact inputs used in this dc system must be secure to momentary application of the full battery voltage. It seems the only way to prevent the contact input from asserting in this situation is by time-qualifying its output (see Figure 10), using two or more consecutive reads.



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Figure 9. Negative DC Grounded System With Load Surge Capacitance

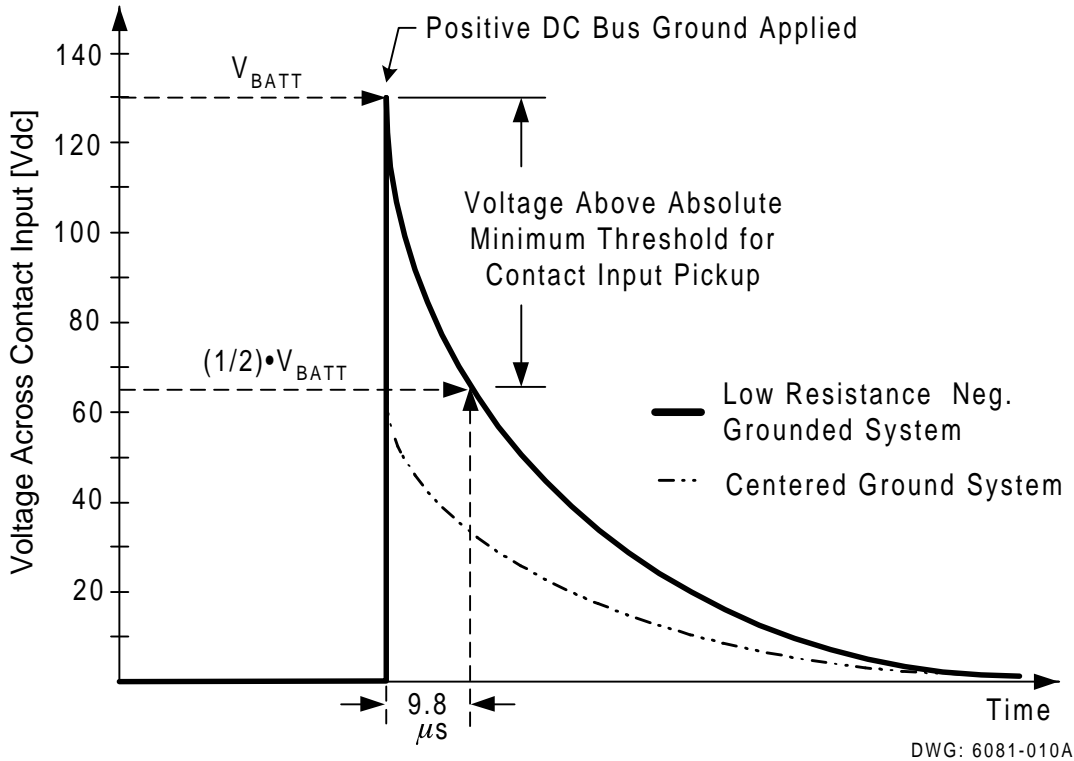


Figure 10. Plot of Voltage Presented to a Contact Input for +DC Ground on a Negatively Grounded and Center Grounded DC System

In such a negative-dc-grounded system, the dc ground scenario of Case 3 is still troublesome because a second dc ground on the +DC rail presents the trip coil with full battery voltage. Unless the application uses a target-indicating relay (which targets the fact that the trip coil drew current), all that anyone would know is that the breaker tripped.

The proposed inadvertent dc ground monitoring feature, when placed in a protective relay, can help the situation. This same relay also monitors breaker status, which is recorded in the relay event recording function. Given these recording and monitoring functions, engineers and operating personnel can access the relay event data to discover the sequence of events that led to the breaker opening:

- Initial inadvertent ground on or near the -DC bus detected by the dc system monitor circuit of Figure 2.
- Simultaneous apparent removal of -DC ground and application of a +DC ground.
- Breaker 52a status changes state from closed to open without the relay or control switch issuing a trip.

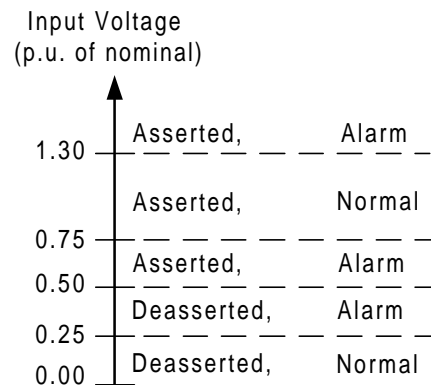
IMPROVED CONTACT INPUT

The contact inputs of digital and static relays convert the open/close status of initiating contacts into a form recognizable by the relay electronics. In traditional relay designs, each contact input has two possible states: asserted when voltage is present across the input and deasserted when voltage is not present across the input. The previous discussion demonstrates that a good contact input should assert only when more than one-half the battery voltage is applied, and only if that voltage is applied for a sufficient time.

In this section, we discuss the benefits of a contact input circuit that actually measures the applied voltage. There are several ways of implementing a voltage-measuring contact input circuit. This paper does not discuss implementation. We simply discuss how such a circuit can help measure and improve the health of the dc system.

Figure 11 shows the various proposed voltage thresholds of a contact input that measures the applied voltage. If the voltage applied to the contact input is between zero and half the nominal voltage, then it is deasserted. If the voltage is greater than half the nominal voltage, then it is asserted.

Figure 11 also shows alarm thresholds. If the measured contact voltage is between one-quarter and three-quarters of the nominal voltage, an abnormal condition exists: the contact input is malfunctioning, significant leakage exists around an open contact, significant resistance exists in a closed contact, or a dc ground exists somewhere between the initiating contact and the contact input. Of these, the latter is most likely. Detecting the existence of a dc ground between a contact output and contact input assists greatly in locating dc grounds.



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Figure 11. Assert/Deassert and Alarm/Normal Thresholds for a Contact Input

If the applied voltage is greater than 1.3 times the nominal voltage, the contact input is either defective, configured incorrectly, is not connected to the right battery, or the battery charger is malfunctioning.

Determining the correct values for the various thresholds can be problematic. Consider a protective relay housed in a circuit breaker cabinet. Table 9, "Rated Control Voltages and Their Ranges for Circuit Breakers," in *ANSI Standard C37.06 : 1987* requires that auxiliary equipment used as part of breaker control be subject to the same voltage limits as those used for the breaker trip and close coils. According to that standard, for a 125 Vdc nominal system, the operating voltage range for trip and close coils is 70 - 140 Vdc. The lower limit allows for drop in the control wiring and target coils that are part of the trip circuit. If the contact input were perfectly

accurate, we could program it to assert at 70 Vdc and still be assured that it would not assert due to a dc ground when the battery is floating at 140 Vdc. If the contact input is not perfectly accurate, then the requirement to operate at 70 Vdc conflicts with the requirement not to assert for a dc ground when the battery is at 140 Vdc.

We can resolve this conflict and decrease the number of false alarms in other applications by allowing the thresholds shown in Figure 11 to track different battery voltages. The battery voltage is measured by the circuit in Figure 2. The vertical axis in Figure 11 would become "Input Voltage, (p.u. \equiv actual battery voltage)." Adaptive thresholds allow the contact input circuit to remain both secure and dependable, even given wide ranges in battery voltage.

For installations using two different voltage battery systems, 125 Vdc for the main control battery and 48 Vdc for the communications equipment, the relay must include two copies of the circuit in Figure 2. Each relay contact input is then assigned a dc monitor circuit and its threshold tracks the respective battery voltages.

Monitoring Coil Path Continuity

Monitoring trip and close path continuity allows us to know when either of these critical circuits experiences an open circuit condition. This is especially important for installations with a single trip coil. We can create a coil path continuity monitor using two contact inputs and the programmable logic found in many microprocessor-based relays.

Traditional trip coil monitoring relays oversee trip coil path continuity with the breaker open or closed. To accomplish this same monitoring, connect two digital inputs of a protective relay as shown in Figure 12. Contact input IN2 monitors the continuity of the trip coil when the breaker is open or closed. When the breaker is open, contact input IN1 also checks the continuity of the wiring from the trip contact to the trip coil.

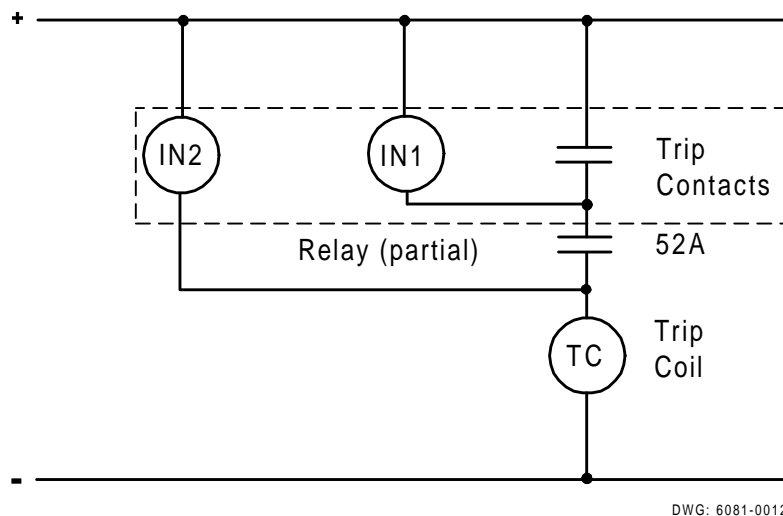


Figure 12. DC Connections for Trip Coil Path Monitoring Logic

Table 1 shows the logic required to monitor the trip coil path.

Table 1. Trip Coil Path Conditions and Relay Input Status

Breaker Position	IN1	IN2	Trip Path Condition
Open	0	0	Loss of Tripping DC or Coil Open
Open	0	1	Trip Path OK
Open	1	0	Monitor Circuit Malfunction
Open	1	1	Monitor Malfunction or 52a Failure
Closed	0	0	Loss of Tripping DC or Coil Open
Closed	0	1	Trip Coil OK, Trip Wiring Bad
Closed	1	0	Wiring Error or 52a Failure
Closed	1	1	Trip Path OK

Legend: 0 ≡ Input Deasserted 1 ≡ Input Asserted

There are only two combinations that do not indicate some sort of problem:

- Breaker open, IN1 Deasserted, IN2 Asserted
- Breaker closed, IN1 and IN2 Asserted

Using a separate contact input called 52a for verification of the breaker position, we have the Boolean equation (where * ≡ Logical AND, + ≡ Logical OR, ! ≡ Logical Invert):

$$\text{TRIP_ALARM} = !(52a * !IN1 * IN2 + 52a * IN1 * IN2)$$

To prevent erroneous pickup of the trip coil path logic, introduce a short time delay to allow the breaker auxiliaries to transfer state and the trip contact to open following a trip.

If contact inputs IN1 and IN2 are the voltage-measuring type discussed above, they can alarm for slowly degrading circuit continuity before the circuit becomes nonfunctional.

Contact Input Debouncing vs Filtering

SCADA systems and Sequence-of-Event Recorders (SERs) have different requirements for contact recognition than do protective relays. An SER should record the time when the contacts first touch, ignoring any subsequent contact bounces. This debounce function is the same as a dropout timer set longer than the maximum bounce-open duration.

As discussed above, a protective relay should consider a contact input asserted only after some time qualification. This filter function is the same as a pickup timer set longer than the maximum transient assertion duration.

We can combine both functions into a single device. The SER function can record the time of first contact closure if the protective relay function subsequently determines that the contact input asserts. This avoids cluttering SER data buffers with erroneous contact input assertions due to contact bounces, dc grounds, or other transients.

USE RELAY OUTPUT CONTACTS TO REPLACE AUXILIARY RELAYS FOR DC CURRENT INTERRUPTION

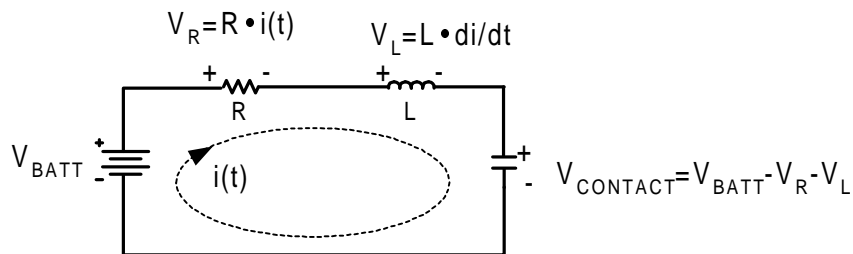
Simplifying dc systems increases their reliability. One easy means of simplifying dc systems is to eliminate components. Given modern digital relay designs with their large number of available output contacts, we can easily eliminate external dc auxiliary relays. We eliminate these relays by supplanting them with the contacts of the digital protection and control relay.

External dc auxiliary relays are used for two primary reasons: to separate dc sources and to increase interrupting duty. Using individual contacts from the protective relay meets the first requirement. The second requirement is only met if the contact from the protective relay has at least the same interrupting capability as the auxiliary relay.

How Metallic Contacts Interrupt DC Current

Metallic contacts in dc control circuits must interrupt dc current. The ability of the contact to interrupt dc current depends on a complex relationship of open circuit voltage, load current, load characteristics, environmental conditions, contact arrangement, and interrupting contact material. Inductive loads are particularly difficult to interrupt. Even when the intended load is resistive in nature, control wiring can exhibit enough inductance to present the contact with an effective load having significant inductance. Cobine [1] gives an excellent discussion of the interruption process from a circuit theory standpoint. However, we found that when the circuit current and capacitance are sufficiently small, the interruption process for some contact materials does not proceed as Cobine described.

Consider the circuit in Figure 13.



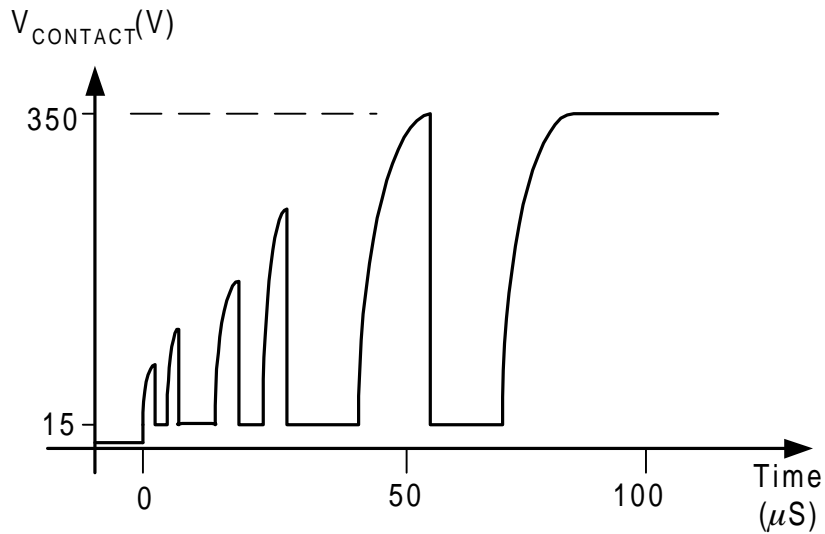
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Figure 13. Typical Inductive DC Circuit

R and L represent the total lumped circuit resistance and inductance, respectively. When the contact closes, the current, $i(t)$, increases gradually to a steady state value, i_{PK} . When the contact opens, $i(t)$ does not instantly decrease to zero, because this implies an infinite di/dt and, therefore, an infinite V_L . The current, $i(t)$, must eventually decrease to zero, or the contact will be destroyed.

To examine how small-gap metallic contacts interrupt dc current, we constructed the test circuit shown in Figure 13. Using this test setup, we tested several contacts suitable for use as protective relay output contacts. All contacts had 0.05 cm gaps. With these gaps, we expected an arcing voltage drop of about 15 V at 0.1 A. (Note that the arcing voltage drop is not the same as the flashover voltage. Theory predicts and tests confirm that these contacts have an open-circuit flashover voltage between 2,500 and 3,000 V.) We fixed the battery voltage at 125 Vdc, and started with $R = 1.25 \text{ k}\Omega$ and $L = 75 \text{ H}$. This produced $i_{PK} = 0.1 \text{ A}$, and a circuit time-constant $L/R = 60 \text{ ms}$.

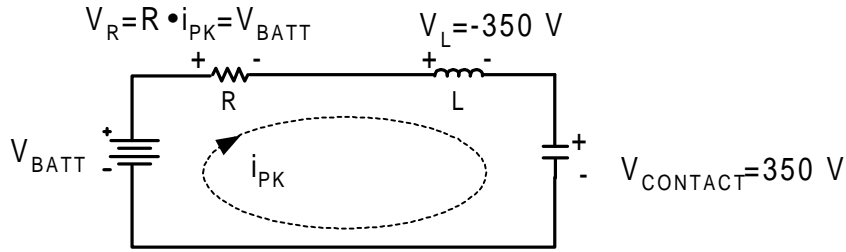
Refer to Figure 14. As the output contacts begin to part at time zero, current through the contacts abruptly chops to zero. However, current through the circuit inductance does not change appreciably. The inductor current rapidly charges the small stray capacitance appearing across the opening contacts. As the stray capacitance charges, the voltage across the contacts increases rapidly until it reaches the flashover voltage of the still parting contacts. At that point, the contacts flashover and begin to arc. As expected, the arcing voltage drop is low, so the contact voltage falls to around 15 V. A few microseconds after the flashover, current through the contacts again abruptly chops to zero, and the voltage again increases rapidly as the inductor charges the contact stray capacitance. However, the contacts have parted a bit more in the few microseconds since the last flashover, so the flashover voltage has increased. The voltage increases until it reaches this new, higher flashover voltage. The process repeats as the contacts separate, with the flashover voltage increasing as the contacts part.



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Figure 14. Typical Contact Voltage During Initial Separation

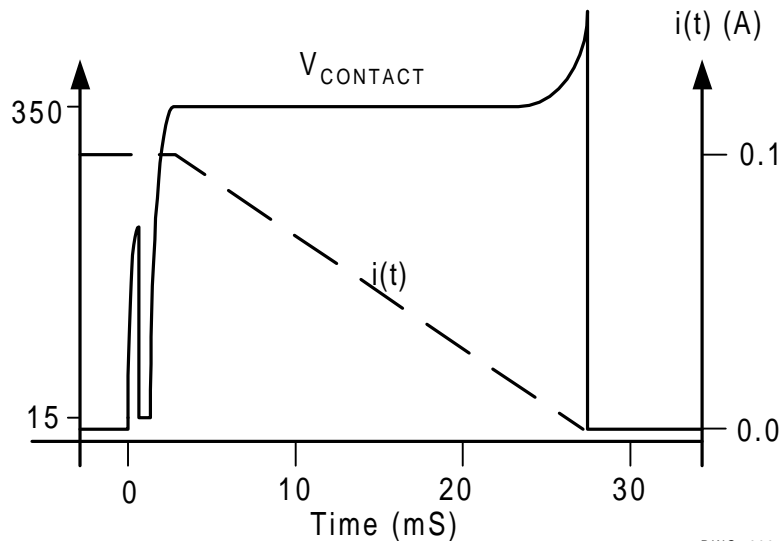
When the contacts separate sufficiently to support about 350 V, flashovers cease. The contact voltage then remains at approximately 350 V. The entire process, from first contact separation until the contact voltage stabilizes at 350 V, takes no more than about 100 μs for the contacts we tested. In that time the circuit current changed very little. At the instant the contact voltage stabilized at 350 V, the circuit current and voltages appeared as shown in Figure 15.



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Figure 15. Circuit Voltages at Transition From Arcing to High-Voltage Conduction

Because the battery and resistor voltage cancel, a stable contact voltage of 350 V produces a voltage across the inductor of about -350 V. This causes current to begin decreasing through the inductor. Eventually, this current decreases to zero. As the circuit current nears zero, $V_{CONTACT}$ increases rapidly to about 350 V. This negative resistance region has negligible effect on the interruption process, because it occurs only near the end of the interruption. Figure 16 shows $V_{CONTACT}$ and $i(t)$ during the interruption process.



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Figure 16. $V_{CONTACT}$ and $i(t)$ During Interruption

If we increased $i_{PK} > 0.5 \text{ A}$, the current chopping/arcing phenomenon shown in Figure 16 (or a stable low-voltage arc) existed until the circuit current decreased below 0.5 A. When the circuit current decreased to less than about 0.5 A, the high-voltage negative-resistance conduction phenomenon occurred and the current again decreased to zero.

The current below which the conduction phenomenon changed from a low-voltage arc to the high-voltage conduction phenomenon varied with different contact materials. With AgCdO (Silver Cadmium Oxide) contacts, the transition occurred at 0.2 to 0.3 A. With gold-plated AgCdO contacts, it occurred at 0.6 to 0.7 A.

Initially we suspected that, as the gold plating burned off the contacts, the gold-plated contact performance would approach the AgCdO contacts. Surprisingly, we found the transition current

increased significantly after the first few interruptions, then slowly decreased over many thousands of interruptions. After 10,000 interruptions, the gold-plated contacts still had a higher transition current than AgCdO contacts.

This discussion leaves a few questions unanswered. What is this high-voltage, negative-resistance conduction phenomenon? What roles do circuit voltage, inductance, and resistance have in determining contact damage during the interruption process? What effect does capacitance have on the interruption process?

To answer the first question, we again referenced Cobine. On pages 250 and 251 of [1], Cobine describes high-pressure glow discharge. High-pressure glow discharge is a low current-density, negative-resistance conduction phenomenon that creates a contact voltage of about 350 V. At one atmosphere in air, glow discharge transitions to a high-current-density arc at between 0.4 and 0.6 A. This description resembles closely the high-voltage conduction phenomenon described above. We believe the high-voltage conduction phenomenon is indeed high-pressure glow discharge.

We expect that contact damage is proportional to the energy dissipated by the contact. How do i_{PK} , V_{BATT} , and L/R affect the energy dissipated by the contacts and, thus, affect contact damage? If we solve the differential equation for current, find when current goes to zero, then integrate the power dissipated in the contact from first parting until the current reaches zero, we arrive at Equation (1).

$$E_{CONTACT} = V_C \frac{L}{R} i_{PK} \left[1 - \left(1 - \frac{V_C}{V_{BATT}} \right) \ln \left(1 - \frac{V_{BATT}}{V_C} \right) \right] \quad (1)$$

where:

$E_{CONTACT}$ = energy dissipated in the contact

V_C = constant contact voltage during interruption

L/R = circuit time constant

i_{PK} = circuit current at the instant the contacts part

V_{BATT} = battery voltage

\ln = natural logarithm

We could have approximated the energy dissipated in the contacts as the energy stored initially in the inductor. That approximation would be optimistic, because it would neglect the energy supplied by the battery during the interruption process.

From (1) we see that contact damage is proportional to circuit L/R and i_{PK} . The only variable of (1) without an obvious relation to contact damage is V_{BATT} . Figure 17 shows how $E_{CONTACT}$ varies with V_{BATT} for $L/R = 40$ ms and for several values of i_{PK} .

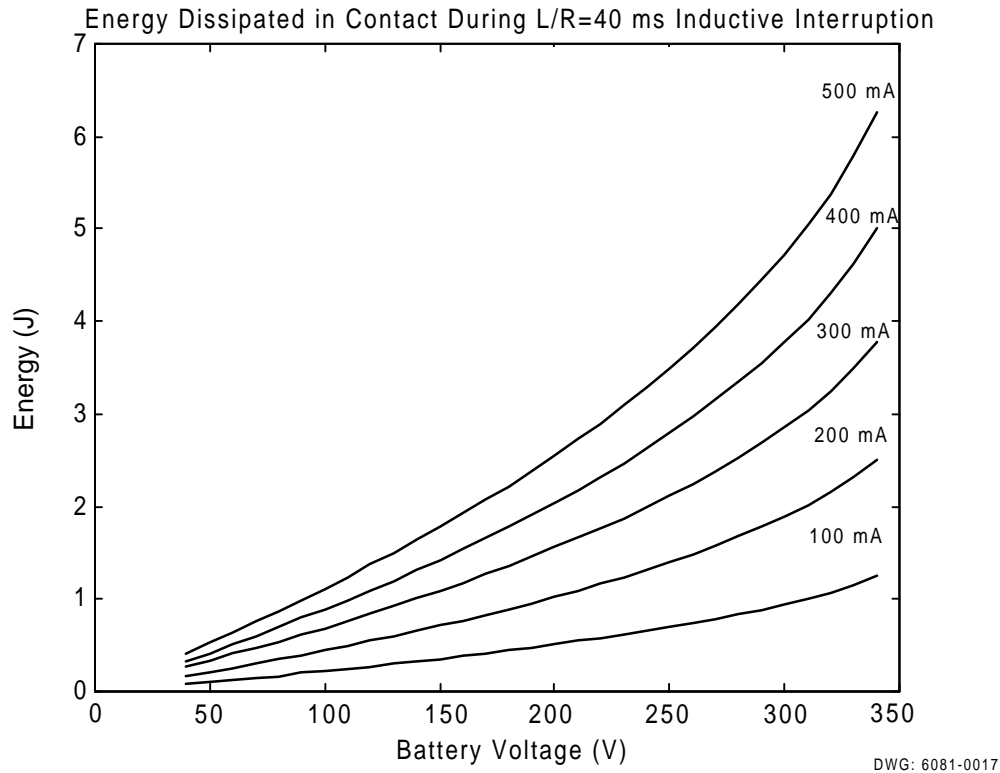


Figure 17. Graph of Equation (1)

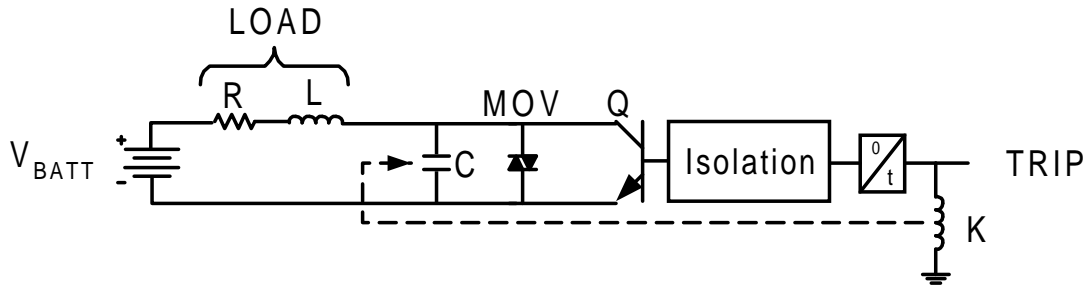
Figure 17 helps relate known contact damage at one current/voltage combination to another current/voltage combination. For example, if we know the contact damage per interruption is acceptable at $V_{BATT} = 125 \text{ V}$ and $i_{PK} = 0.4 \text{ A}$, then we would expect equal and, therefore, acceptable damage at 250 V and about 0.15 A .

If the circuit contains enough capacitance, the energy dissipated by the contacts changes because the waveforms of Figure 14 and Figure 16 change. In Figure 14, the time required for the circuit inductance to charge the capacitance to the flashover voltage increases. This gives more time for the contaminants introduced into the gap by the arc to dissipate, and for the contacts to cool. If the contaminants dissipate and the contacts cool sufficiently, glow discharge does not occur. Each time the arc extinguishes, the circuit inductance and capacitance begin to ring. If the peak of the ringing voltage is less than the flashover voltage of the contacts, then the arc does not reignite. Interruption is complete after the ringing dies down. This reduces significantly the energy dissipated by the contacts. In this kind of interruption, the circuit resistance dissipates the vast majority of the energy stored in the inductor.

Interrupting Large Inductive DC Currents

To interrupt higher dc currents, we cannot rely on glow-discharge. We must either create a sufficiently large arc voltage by increasing the contact gap, or rely on the circuit capacitance to hold the peak ringing voltage to less than the open contact flashover voltage. We do not want to rely on circuit capacitance, and contacts with larger gaps tend to have slower operating speeds.

Figure 18 suggests another method of interrupting large inductive dc loads, while actually increasing the operating speed. The circuit of Figure 18 shunts current around the contacts (C) until they reach full separation, then clamps the ensuing inductive kick voltage to a level that the open contacts can withstand.



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Figure 18. Application of High-Speed, High Interrupting Contact Output

In Figure 18, signal TRIP energizes the control coil K for the main metallic contacts. At the same time that TRIP energizes K, it also turns on transistor Q through the isolation device. Transistor Q turns on immediately and begins to conduct current through the load L and R. After some time the metallic contacts of K touch and begin to carry the load current. When properly designed, this circuit has a make-time of about $1 \mu\text{s}$ and the same continuous carry capacity as the metallic contacts.

A time-delay dropout timer keeps Q on for time t after TRIP turns K off. Time t allows the contacts of K to separate fully before Q turns off. When Q turns off, it forces the inductive current to flow through the MOV. Current flowing through the MOV causes it to break down and clamp at about 400 V. This creates negative voltage across the inductor, which forces the inductor current toward zero. Because the fully open contacts are capable of withstanding 400 V, no flashover, arcing, or glow discharge occurs. Also, the metallic contacts dissipate near zero energy. The MOV and circuit resistance absorb all of the energy stored in the inductor and produced by the battery. The contacts dissipate essentially zero energy, and therefore suffer negligible damage. In fact, this circuit has interrupted a 10 A, $L/R = 40 \text{ ms}$ inductive load at 125 V more than 10,000 times with no appreciable damage to the contacts.

Equation (1) gives the energy dissipated in the MOV for each interruption where V_C now is the MOV clamping voltage (400 V in this case). The energy is directly proportional to L/R and i_{PK} . Figure 19 shows how much energy the MOV absorbs for a single interruption of a 40 ms inductive load.

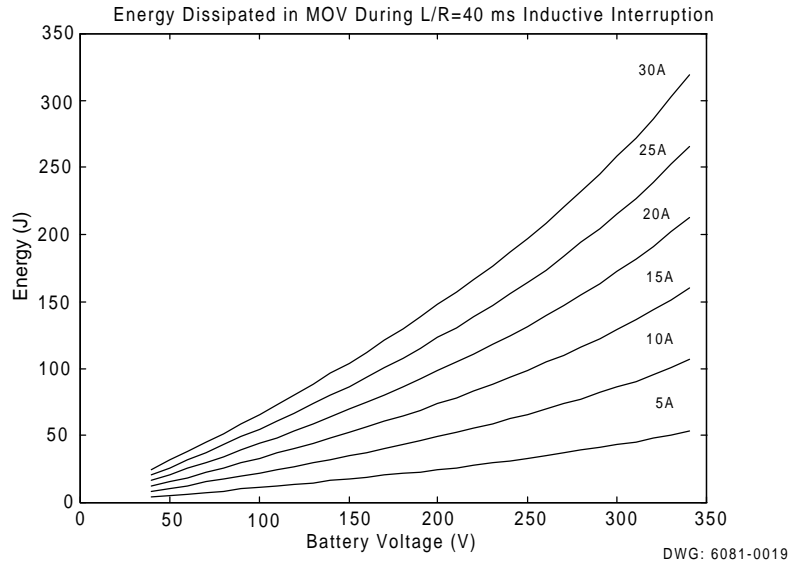


Figure 19. Graph of Equation (1) for Circuit in Figure 6

The energy dissipated by the MOV is cumulative, if the MOV is not given time to cool. Such might be the case if the contact in question is interrupting trip or close coil current during a high-speed reclose sequence. For instance, given an MOV rated to dissipate 100 Joules, the circuit could interrupt a 10 A, 40 ms inductive load at 125 V four times in rapid succession (within one second). Following this sequence of high-current interruptions, the MOV must then be allowed to cool.

If the interruption is not repetitive, then the full energy rating of the MOV can be used for a single interruption. For example, if the MOV energy rating is 100 Joules, then the circuit can interrupt approximately 30 A of L/R = 40 ms inductive load at 125 V, or about 15 A at L/R = 40 ms inductive load at 250 V.

High-speed, high-interrupting output contacts have many uses.

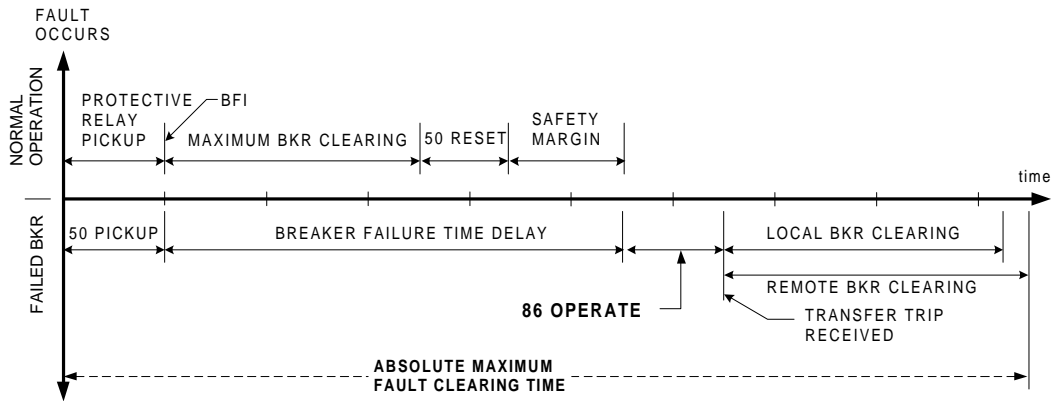
Decrease Relay Operating Speeds (Trip Direct)

Relay operating time is the total time required to detect the fault and close the tripping output contacts. Open-to-close operating time for electromechanical output contacts is approximately 3 - 4 ms, or nearly a quarter cycle, at 60Hz. Use of the fast, high-current interrupting contacts described above avoids adding this one-quarter cycle to the tripping time. This increase in tripping speed occurs without loss of protection scheme security.

Increase Breaker Failure Margins (Relegate 86 to Hand-Reset Device)

From Figure 20, we see a cascade of events and the associated operating times of breaker failure relaying. All of these events must occur within the absolute maximum system fault clearing time. We can virtually eliminate the 86 (lockout) operating time by tripping each local breaker

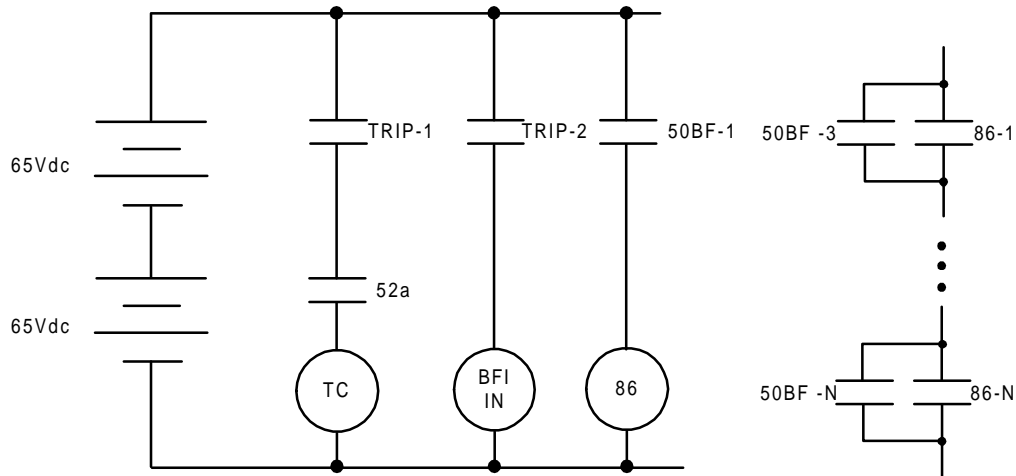
directly from the breaker failure relay using the high-speed, high-current interrupting output contacts described above. This saves approximately one cycle. Given this time savings, you can decrease the absolute maximum fault clearing time. Alternatively, you may increase the breaker failure timer to increase security.



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Figure 20. Basic Breaker Failure Scheme Timing

Figure 21 shows a typical dc schematic diagram where the breaker failure relay (or relay including breaker failure functionality) parallels its trip outputs with the existing 86 outputs. Notice that inclusion of the 86 device retains the mechanical hand-reset feature.



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Figure 21. Typical Breaker Failure Schematic Using High-Speed Output Contacts

Stuck Breakers for Trip Direct Applications Should Not Destroy Output Contacts

In applications where the protective relay trips the breaker directly, the 52a contact normally interrupts the trip coil current. The exception to this is a mechanically stuck breaker. For such events, the 52a contact never opens. When the breaker failure scheme clears the bus, the protective relay senses removal of the fault and opens its tripping contacts. Because the 52a

contact is still closed, it is the tripping contacts which must interrupt the trip coil current. In such a case, the direct tripping contacts must be rated to interrupt trip coil current. An exception to this is where a “b” contact from the 86 is placed in series with the tripping contacts. For such applications, the 86 contacts perform the interruption, but only if the tripping contacts are guaranteed to drop out after the 86 operation.

CONCLUSIONS

1. An inadvertent dc ground must be detected; the second ground can operate the dc system protection and thus deenergize all connected loads. We discuss a simple means of including dc ground detection within a protective relay.
2. Contact inputs must have a minimum voltage threshold, for security during dc grounds. This minimum voltage threshold is at least half the battery voltage. We also introduce a new contact input circuit that measures the voltage applied to the contact input terminals. In addition to avoiding false contact input assertions during dc grounds, this measurement capability assists in locating the dc grounds.
3. DC system capacitance can operate auxiliary, trip, and close coils. In the cases we reviewed, stray and surge capacitors supplied the energy required to operate these coils. Capacitance in a dc control circuit may be necessary in some instances, but we strongly recommend removing capacitance where possible.
4. When loads connect directly to the -DC bus, negative-grounding the dc system avoids the problem discussed in 3. above. We discuss means of automating the tests for inadvertent negative dc grounds in these systems.
5. The voltage presented to contact inputs can approach full battery voltage for +DC grounds on negative-grounded systems. In such systems the contact inputs must be time-qualified to maintain security.
6. Monitoring the continuity of trip and close circuitry is important. We show a simple means of implementing this monitoring using contact inputs and simple programmable logic.
7. When interrupting highly inductive current, output contact damage is proportional to interrupted current and the L/R of the circuit. Properly designed metallic contacts reliably interrupt as much as 0.5 A of inductive current.
8. Combining a solid state device with metallic contacts creates a hybrid output circuit. These hybrid relay contacts can reliably interrupt 30 A or more in very inductive circuits. This new capability simplifies the dc system by eliminating many dc auxiliary relays.
9. The nearly instantaneous operating speed (1 μ s) of the high-current interrupting contacts increases protection speed without sacrificing security.

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- [1] James D. Cobine, *Gaseous Conductors: Theory and Engineering Applications*, Dover Publications, Inc. New York, 1958.
- [2] J. L. Blackburn, *Applied Protective Relaying*, Westinghouse Electric Corporation, Relay-Instrument Division, Newark, N.J., 1976.

BIOGRAPHIES

Jeff Roberts received his BSEE from Washington State University in 1985. He worked for Pacific Gas and Electric as a Relay Protection Engineer for more than three years. In 1988, he joined Schweitzer Engineering Laboratories, Inc. as an Application Engineer. He now serves as the Research Engineering Manager. He has written many papers in the areas of distance element design, sensitivity of distance and directional elements, directional element design, and analysis of event report data. Mr. Roberts holds numerous patents and has other patents pending. He is a member of IEEE.

Tony J. Lee received his B.S. degree in electrical engineering from Washington State University in 1987. Mr. Lee then worked for Texas Instruments in Dallas, Texas from 1987 through 1991, when he joined Schweitzer Engineering Laboratories, Inc. as a hardware design engineer. He presently holds the position of Research Engineer at SEL. Mr. Lee holds two U.S. patents and several foreign patents regarding arc suppression and has several patents in process.