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When is a Good Ground Not?

Poor performance in high current carrying conductors (especially grounds) can be difficult to diagnose. Investigations into poor alternator voltage regulation or starter performance always begin with conductors other than grounds. Ground pathways are often overlooked as a contributor to poor system performance . . . especially in metal airplanes where the whole airframe is "ground."

It's important to remember that for every electron that leaves the battery another electron has to return via the other terminal; the same currents that flow in the power distribution wiring also flow in ground return conductors. Let's take a look at how a small resistance in wiring and electrical system components can stack up to trash what might otherwise be satisfactory performance of an electrical system.

A Few Milliohms Go a Long Way

A pretty decent flooded (wet), lead-acid battery will have an internal resistance of about 10 milliohms. It's difficult to make a joint between any two conductors that's much better than 0.5 milliohms per joint without welding. Consider 2AWG wire with a resistance of .156 milliohms per foot. In a Long-Ez the path from nose to tail can be about 20 feet round trip so $20 \times .156 = 3.22$ milliohms resistance in the wire alone. How about the contactors? Hm . . . two contacts in series held together by an energized electromagnet might be 1 milliohm per contact so there's another 4 milliohms total. Add 'em up . . .

Battery resistance	10.0 milliohms
2 Contactors	4.0 milliohms
15' of 2AWG wire	3.2 milliohms
Bolted Joints (4 wire segments with 2 joints at 0.5 milliohms each)	8.0 milliohms
Total resistance	25.2 milliohms

It is difficult to imagine how so small a resistance can make any difference. Consider that for all but the small-

est engines, a starter can easily draw over 200 amps! Ohm's law says that for every ampere of current pushed through 1 ohm of resistance, there will be 1 volt of drop across the resistor or $\text{Volts} = \text{Amps} \times \text{Ohms}$. 25.2 Milliohms time 200 Amps equal 5040 Millivolts or 5.04 volts of drop. If we started with a 12.5 volt battery, we'll now see about 12.5 minus 5.04 or 7.46 volts at the starter terminals. We've lost over 1/3 of our cranking energy in the trip from battery to motor! On a cold morning, the engine is stiffer and battery resistance goes up. Just when the engine would benefit from more cranking energy, the battery's ability to deliver it lessens.

The resistance of wire, contactors and battery are fixed, we have no control over them and they are never zero. Also note that bolted joints make up a significant percentage of total drop. Even minimizing wire length has a rather small effect compared to reduction in number of bolted joints. Numbers in real life may vary quite a bit from those I've used in the example. The point to be made is that while the resistance values we're discussing are tiny; pushing electrons through the system at 200+ amps makes every milliohm count. Some care in selection and assembly of parts can reduce the over all resistance numbers.

In Figure 1, I've illustrated the most important wires in the airplane. The first wire I install is from battery minus to a firewall ground block thru-bolt.. The second wire runs from ground block thru-bolt to crankcase. For canard-pushers with forward batteries, a instrument panel ground block is wired to battery minus lead in the nose as shown. Ground points for equipment in the rear are provided with a second ground block mounted on one or both sides of the firewall. Some of the worst performing starters are found on metal airplanes where battery ground lead is bonded locally to airframe. Engine is bonded to mount by jumpers around the vibration isolators and the mount is "grounded" to airframe through its mounting bolts. New airframes and other structures holding engines on are pretty good substitutes for wires when new. A few decades of age and improper maintenance can drive ground path resistance up dramatically from that which left the factory.

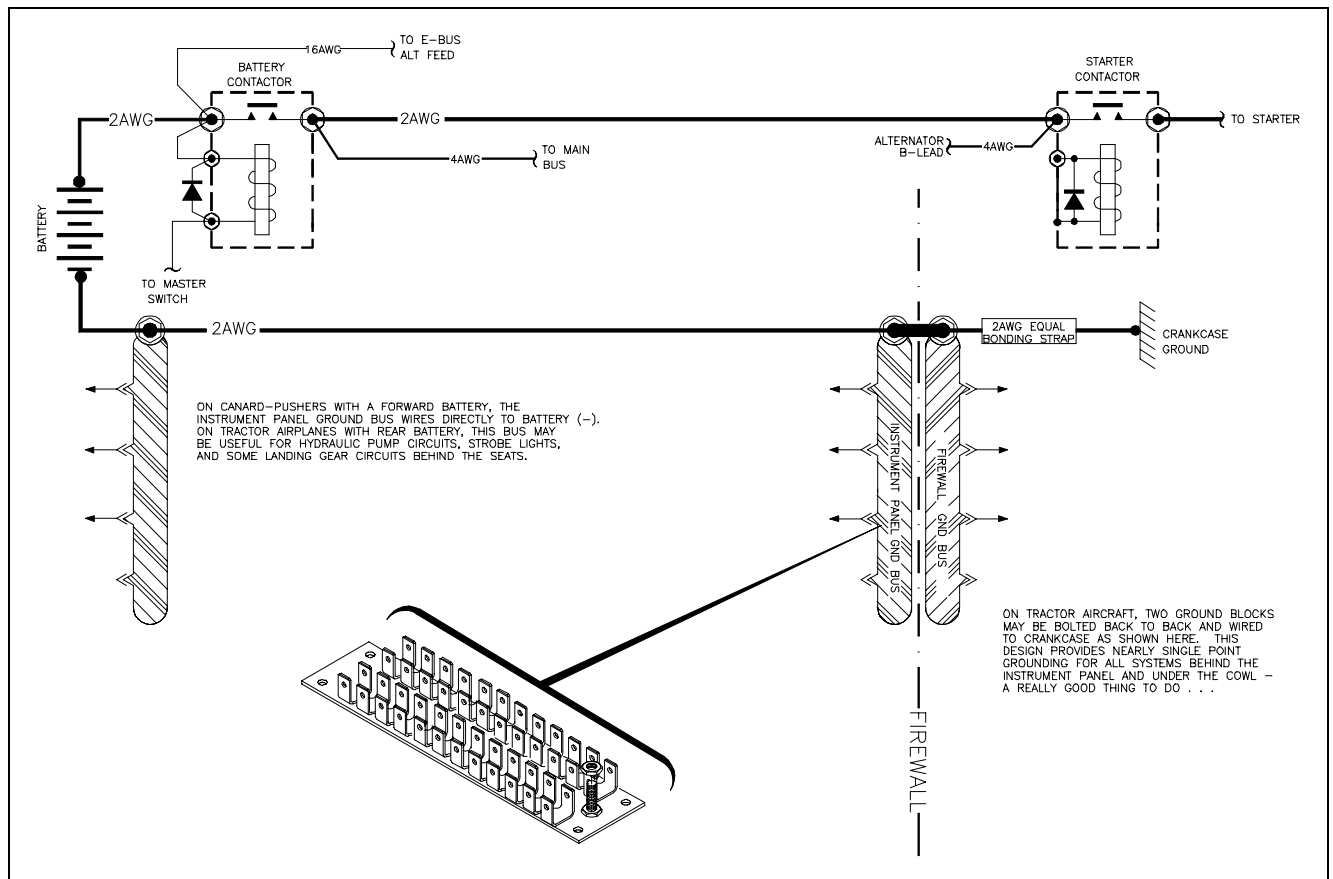


Figure 1. The Most Important Wires in the Airplane.

Engine mounts should be used for attaching engines to airplanes. They are not good substitutes for an electrical bond strap connecting the crankcase to a firewall ground stud.. This grounding architecture I recommend here optimizes engine cranking performance and minimizes ground loop problems which may degrade alternator voltage regulation, cause noises in an audio system or radios and affect the accuracy or stability of engine instruments.

If the battery and engine are on opposite ends of a composite airplane it's important to run battery (+) and (-) cables right next to each other as they traverse the cockpit and instrument panel areas. Tie-wrap them together every 6 inches or so. Some Ez builders have run (+) and ground down opposite sides of the fuselage with some bizarre results.

Several kit manuals suggest that a couple of studs on a firewall ground block are sufficient for termination of all system grounds. This is poor practice. As single stud is responsible for many grounds . . . a broken bolt or loose nut causes problems in multiple systems. The ground block I've illustrated is a special product I designed and asked B&C Specialty products to manufacture. 0.25" wide, fast-on tabs are sweat soldered to a piece of sheet brass. A 5/16" BRASS stud is used to carry a good electrical ground from the cockpit area to the engine

compartment. There are sufficient ground points to give each system all the structurally independent grounds it needs without having to share. I highly recommend its use.

Minimizing high-current path resistance has another benefit: Many airplane designs don't need a lot of battery capacity but some builders find that a larger battery (lower internal resistance) improves cranking performance. A number of single-engine Pipers have 35 ampere-hour batteries in the tail . . they didn't need the extra capacity but the lower internal resistance improved cold weather cranking operations. B&C holds STCs for replacing a 35 ampere-hour, 30 pound battery in many Pipers with a 25 ampere-hour, RG (recombinant gas) battery. The new battery has a 5 milliohm internal resistance and 22.5 pounds weight. Cranking performance is greatly improved in spite of the new battery's small and lighter package. Keeping wiring and component resistance down allows a builder to consider very light batteries that might otherwise be unsuitable if they're sandbagged with unnecessarily high cranking path resistance.

Introducing the 4-Wire Ohmmeter

Measuring the quality of any low resistance conductor path would appear to be difficult. Common multimeters do not read out in fractions of milliohms. A few years ago I was investigating an accident where electrical ground

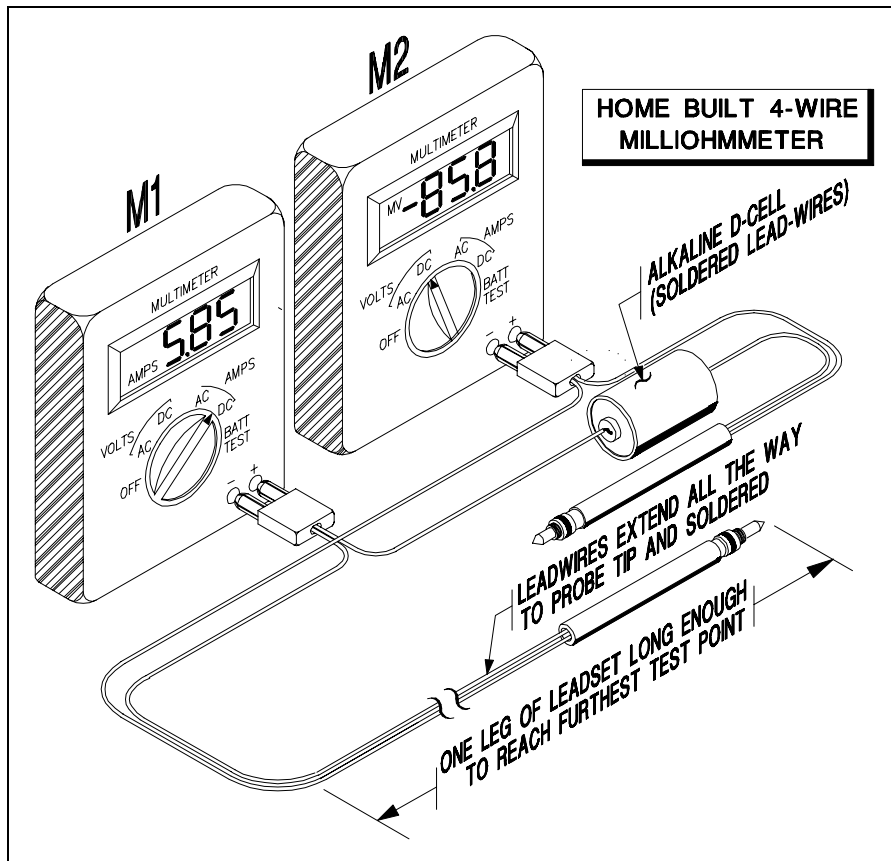


Figure 2. Poor Man's 4-Wire Milliohmmer .

conductivity was in question; measurements in the milliohms were needed. I visited a local Radio Shack and bought **two** digital multimeters. One needed a capability of reading current on the order of 10 amperes or more. The other was for reading millivolts; hopefully to the nearest 0.1 millivolt.

I also purchased a D-size alkaline cell, some 18 gauge lamp cord, test probes and banana plugs. The man behind the counter loaned me a soldering iron and I built the rig shown in Figures 2 and 3; a poor-man's 4-wire milliohm meter. You may be tempted to construct this fixture using spring-loaded battery holder for the D-cell. I recommend soldering leads right to the cell; battery holders are not designed to carry the 5-10 amp currents that will flow while this test fixture is in use. Clean the cell end areas to be soldered. Get on and off quick with a hot iron.

When I touch the two probes together I've placed a dead short on the D-cell . . . well, almost a dead short. Obviously, the cell has an internal impedance which limits the current that a shorted cell will deliver. The wire between cell and probes has some resistance too. As it turned out, when the two probes were touched together, multimeter M1 indicated about 7 amps.

Figure 3 shows how one multimeter is set up to measure the voltage between the two probes through a path that is

independent of the D-cell current path. The operative feature here is that no voltage drop will occur along the voltage sense leads and multimeter M2 will read the voltage between the two probes irrespective of the voltage dropped along the D-cell's current path.

When making resistance measurements between a tailcone mounted battery and a nose mounted engine's crankcase, the task may require two people. The accident case I was working questioned the quality of a ground on a Rotax alternator stator assembly. I pushed one probe down very firmly on the stator laminations while probing the crankcase with the other, a current on the order of 7 amps flowed in the ground path between stator and crankcase. Let's assume the M1 reads 6.8 amps voltmeter reads 9.6 millivolts. Ohms law sez ohms = volts/amps so $.0096/6.8 = .00141$ or 1.4 milliohms. In this case, the measurement showed that Rotax's installation of the stator had sufficient

integrity to exonerate it from having caused the engine to lose power.

There are some pretty nifty clamp-on type ammeters for dc current. Why not just measure starter current and the voltage drop while cranking? Several reasons. First, starter current is not steady; compression strokes cause it to gyrate in a manner that prevent stable readings from a digital instrument. Voltage-drops due to resistance are equally difficult to measure. They thrash around in sympathy with current fluctuations. The neat thing about this

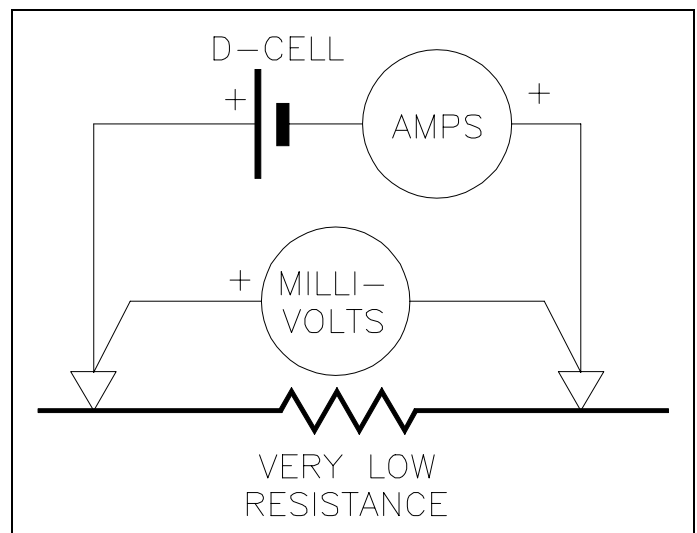


Figure 3. 4-Wire Ohmmeter Schematic.

measurement technique is that it utilizes ordinary multimeters that should already be in your toolbox. Well, at least one. You might have to borrow an additional instrument to do these measurements. The technique requires an easily fabricated battery harness and probes. Being an independently excited measurement system allows measurements on a “cold” and/or incomplete electrical system,

The same measurement can be applied to components of the positive power path as well. Remember, we’re measuring the resistance of wire plus bolted and crimped joints. When measuring the resistance of the lead between battery contactor and the starter contactor, probe the bolt ends on each contactor. Obviously, this same test fixture can be used to check path resistance on any other circuit on the airplane and produce results with great integrity. FBOs will often have the instruments necessary to set up this fixture but not one in a hundred knows how to do it, how it is used or what the readings mean. The 4-wire ohmmeter is a standard inspection and diagnostic aid in my toolbox.

Significance of Measurements

In examples discussed so far, we’ve been talking about cranking currents along with the fat wires and components that are subject to those currents. In these cases, a few milliohms of unwanted resistance can throw away a significant portion of the system’s operating power.

Another common victim of resistance pollution is the alternator’s voltage regulator. Consider the wiring and all the components in the wiring between the ship’s main bus and the voltage regulator on many certified airplanes. In some of the older Cessnas, it’s not uncommon to travel through a circuit breaker, field side of a DC Master switch, overvoltage relay and then out to the regulator. The production harness includes several AMP Mate-n-Lock connectors with pins that are NOT gold plated.

Over time, every crimped joint, mated pin, clamped up ring terminal, switch contact and relay contact increases its resistance with age. No one device goes up a lot. I think I counted something like 16 assembled connections in the alternator’s field power path on one particular Cessna.

An alternator’s field draws about three amps maximum. Let’s suppose that the field circuit resistance is something on the order of 100 milliohms. A 3-amp current draw will induce a 300 millivolt drop in the pathway from bus to regulator. This can have two profound effects. First, the regulator thinks the bus is running 300 millivolts lower than true and jacks up the

alternator’s output to compensate for it. This means that as the alternator’s load is increased, field current goes up and the regulator’s perceptions of true bus voltage are increasingly in error.

Normally, when you load a device or system with heavier current, you expect resistance associated with the system to cause voltage to go down. However, when resistance is included inside the control loop of the voltage regulator, an increasing load on the system causes the alternator’s output to rise instead of fall. This is called a “negative resistance” condition. If it progresses far enough with some regulators, the system will break into oscillation.

The problem manifests itself as a wiggling ammeter or perhaps agitated panel lights. More than one airplane exhibiting these symptoms has suffered replacement of alternators and/or regulators with no or temporary relief. Sometimes the problem goes away when the mechanic replaces the DC Power Master switch (usually the infamous split-rocker). What the mechanic generally doesn’t know is that regulator instability is caused by small build-ups in most of the field supply line’s components. Replacing one component may bring total resistance down to a stable condition but the problem returns sooner than necessary because all of the components continue to age and drive circuit resistance up.

The 4-wire milliohmmeter can be used to measure field supply resistance between bus bar and regulator’s input terminal. 30 milliohms maximum is a good value to shoot for (approx 100 mV maximum uncertainty for regulation at 3 amps field draw). Our wiring diagrams with crowbar OV protection, fusible link feeds from the bus and NO intermediate connectors are examples of feedpath resistance reduction by design. Bus to regulator resistance of the circuits shown will be easily less than 30 milliohms and should stay that low for very long periods of time.

If you’re having difficulties with voltage regulator stability, the 4-wire milliohmmeter can help you deduce (1) if instability is likely to be caused by an abundance of milliohms between bus and regulator and (2) ferret out the most significant contributors to the problem.

I hope this discussion has adequately illustrated the situations where very small resistance values can have a profound effect on system performance. Resistances so small, that the ordinary multimeter is incapable of resolving it. Finally, that you’ll take advantage of this simple technique for doing meaningful measurement and diagnosis of some electrical system problems that very few mechanics know how to diagnose, much less fix.

Fly comfortably . . .