LEAKAGE AND GROUND CURRENTS: MEASUREMENT TECHNIQUES

by

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Overview

Since the early days of power quality analysis, the measurement of low level currents on ground conductors, ground rods, conduits, signal cables, and other physical structures has proven to be a useful diagnostic tool. Such currents can be the direct cause of problems, such as magnetic fields caused by net currents, or safety issues related to leakage currents. In other cases, the ground currents are not in and of themselves a problem, but can be symptoms of grounding problems in the facility infrastructure or equipment. Locating the source of these currents, understanding the nature of the currents, and reducing the currents, can be a significant contribution towards improving the grounding system.

This paper focuses on the measurement of these low level currents. For simplicity's sake, these currents will be called "ground currents" from this point, even though the actual current being measured might be neutral currents, shield currents, net currents, conduit currents, leakage currents, etc.

A discussion of the source, causes, impact, and resolution of ground currents, while worthwhile, is beyond the scope of this paper. Such issues will be touched on as needed in the discussion of diagnostic and measurement techniques, but a comprehensive discussion of ground currents will be left for another time.

Definitions

Three primary categories of low-level currents will be discussed in this paper.

Ground Currents are any currents that are flowing on grounds. Grounds can be chassis grounds, safety grounds, shields, raceways, or reference grounds. In general, safety grounds have ideally no current. However, many normal and abnormal conditions may create ground currents – both at power frequencies as well as at other frequencies. Ground currents may be sourced from the source being considered, or from other sources in the facility, and it is often difficult to identify the specific cause of ground currents.

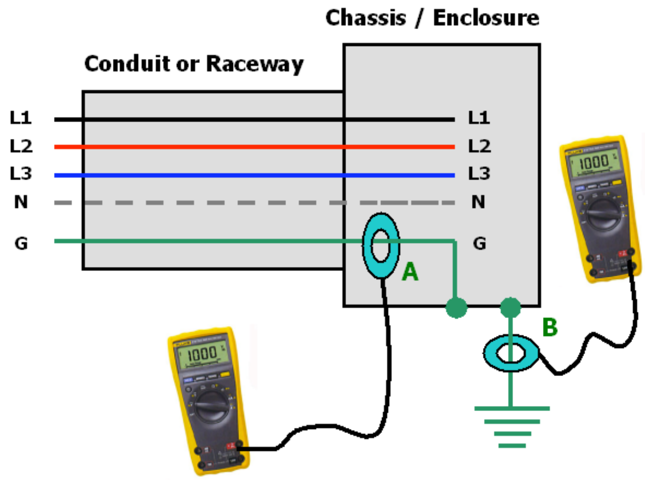
Leakage Currents are currents that are derived from normal and abnormal connections of the source to the safety earth. In general, leakage currents are more easily identified that ground currents. Leakage currents often flow back to the source through the associated ground conductor. However, they may also flow through alternate ground paths, contributing to ground currents throughout the building.

Net Currents are non-zero summary currents that flow on conduits, feeders, or branches. They can be related to ground currents, leakage currents that return to the source through parallel ground paths, or neutral currents that flow to the source through parallel ground paths.

These three types of low-level currents, while often related, must be measured and investigated differently – the types of troubleshooting and appropriate solutions vary widely.

Ground current? Yes – but it's more complicated than this . . .

Ground Currents



Basic ground currents are measured on a ground conductor, typically colored or marked green, or a bare conductor. If reviewing a set of power monitor data, or remotely reviewing site measurements made by another individual, this is the most probable type of low-level current measurement that is made.

At right, ground current measurements are being made on the equipment safety ground A as well as on a supplemental ground connection B. Usually, measurement point A is what people refer to when discussing ground currents.

The problem with this type of ground current measurement is that it is incomplete. Assuming a normal electrical system (with no attempts made to insulate equipment, raceways, etc.) there are other paths for ground current: raceways, conduit, mounting hardware, mechanical chassis connection, and signal connections. Each of these paths may be a sufficiently low impedance parallel ground path to take a significant portion of the ground current. As a result, simply measuring the ground current at point A (for instance) provides limited information about the total ground current that may be flowing.

Ground Loops

Ground loops are the result of alternate or parallel connection paths from the equipment back to the facility ground. These might be any of the following:

- Deliberate alternate grounding paths (ground rods, redundant grounds, connections to a ground grid or other electrode)
- Raceway or Conduit grounds
- Mechanical mounting of the equipment to the facility structure or to other grounded equipment
- System interconnection (signal or data) – on shields, signal commons, or distributed power cables.

If you are tracking down unwanted or excessive ground currents, keep in mind all of these pathways – the ground currents do not necessarily follow the most obvious paths. In some case (e.g. – mechanical mounting) you may need to find low ground currents on all other paths, to prove that the mechanical mounting is the source of high ground currents.

Grounding for Power Quality

In many cases, alterations to the more conventional grounding system may have been made for the purpose of improving grounding: reducing ground impedance, breaking or minimizing ground loops, reducing ground currents, redundant grounds to reference subsystems to each other.

Such alterations might include:

- Insulated fittings on raceway or conduit
- Full sized or oversized ground conductors
- Isolated ground receptacles and running a separate, dedicated ground
- Short bonding jumpers from equipment chassis to a ground reference, ground gird, or other nearby equipment cabinets
- Supplemental ground connections to facility steel, ground electrodes, etc.

The intent of these modifications, the efficacy of these, and the proper application therein, will not be discussed here. But from a measurement and diagnostic perspective, be aware that these measures may be in place – and that measurements of ground currents may be made before and after such alterations have been made, in order to prove (or disprove) that the changes have been made and are effective.

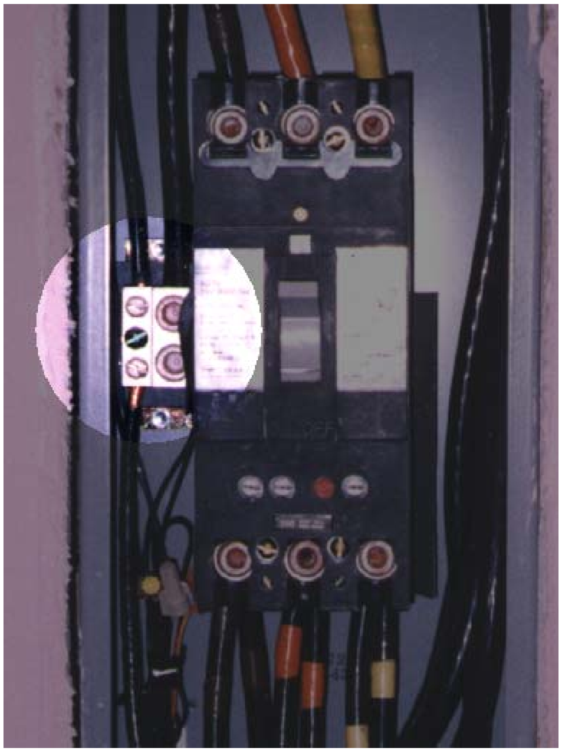
Wiring Errors

A likely source of ground currents can be wiring errors, specifically related to the inadvertent connection of safety grounds or reference grounds to current carrying conductors. Two common wiring errors are worth mentioning briefly:

1. Improper connections of ground conductors to neutrals (or "grounded conductors", as defined in NFPA-70) will permit normal neutral currents to flow in the grounding system. Such currents will flow in the ground conductor (if present) that is run with the neutral back to the source, but will also flow in ALL ground conductors as well as chassis, shields, conduit, etc. – seeking a path back to the original N-G bond.

   There are two proper places for the neutral and ground to be bonded – at the service entrance, and on the secondary side of separately derived sources. Other locations (circuit breaker or disconnect boxes, primary side of transformers, autotransformers, etc.) often need to be hunted down and eliminated.

2. Improper use of the ground as a return path, either through the inadvertent mixing of neutral and ground conductors, or the deliberate use of the ground (say, as a return for a single phase control circuit, pulling 277 VAC from a 480 VAC source)



*Improper neutral-ground connections,
as seen in this circuit breaker enclosure,
are a prime cause of improper ground currents.*

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Leakage Currents

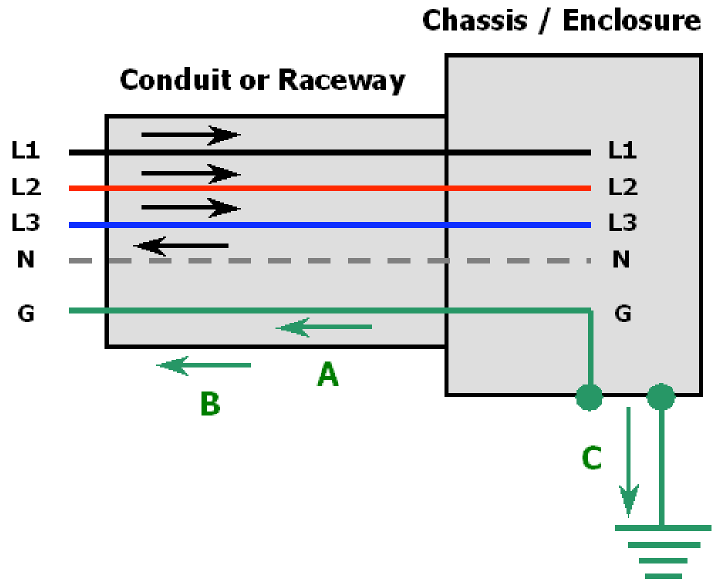
Leakage Currents are currents that flow from phase to ground, typically related to capacitance to ground. This capacitance may be normal (e.g. - filtering), parasitic, or related to a component failure, wiring problem, or insulation breakdown.

Normally, the vector sum of currents L1 + L2 + L3 + N = 0, with all currents canceling.

Leakage Current is the imbalance in these currents. It may flow in the equipment safety ground (A), the conduit or raceway (B), or other paths to ground (C).

Low-level leakage currents (normal) may be related to filters connected to ground, or to parasitic capacitance.

Higher-level leakage currents (abnormal) may be related to wiring errors, insulation breakdown, or component failure.



A familiar example of leakage currents can be found in the home Ground-Fault Circuit-Interrupter (GFCI) where a leakage current of 5 mA or higher will cause the interrupter to trip and remove power. The GFCI operates by measuring leakage currents. Typically, a GFCI is applied in areas of higher risk due to wet or damp conditions (bathrooms, kitchens, basements, exterior receptacles, etc.). The requirement and proper use of GFCI protection can be found primarily in NFPA-70 - 210.8: *Ground Fault Circuit Interrupter Protection for Personnel.*

Another common measurement of “leakage” can be found in large building where Ground-Fault Protection (not GFCI) is required for large feeders (1000A or higher, greater than 150 VAC to ground). This is a much higher setting (up to 1200 Amps) and is intended to provide circuit protection in the event of an arcing fault to ground, where the primary overcurrent protection may not function. NFPA-70 - 230.95: *Ground Fault Protection of Equipment* describes this type of protection.

In patient care environments such as hospitals, clinics, etc., more stringent leakage current limits are set (NFPA-99 in the United States, among other standards). Such leakage current limits are 5 mA (for fixed equipment) or 300 uA (cord-connected equipment). NFPA-99 9-2.1.13: *Manufacturers’ Tests for Safety of Patient Care-Related Electrical Appliances*.

The key with leakage currents is that these currents are not coming from “out there, somewhere” but instead are sourced in the same place as our equipment is fed, and follow a clear pathway from source, through the equipment, and back to the source through the grounding system. As a result, accurate measurement of these leakage currents is often possible – and as a result diagnosis of problems and resolution of these is also more easily done.

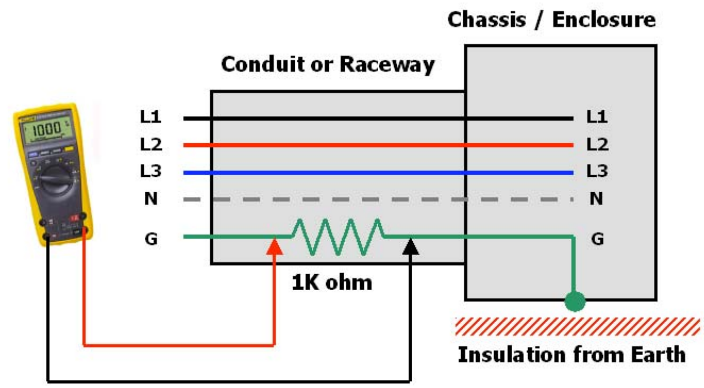
Measuring Leakage Currents

Historically, leakage current measurements (as specified in NFPA-99, for example) involve the insertion of a burden resistor in the ground conductor, and a measurement of voltage across this resistor.

NFPA-99 specifies the test set-up to measure leakage current as simplified at right.

In reality, the 1KΩ resistor shown here is a filter network that attenuated frequencies greater than 1 KHz.

This set-up works for testing small, portable equipment, which can be physically insulated from accidental earthing.

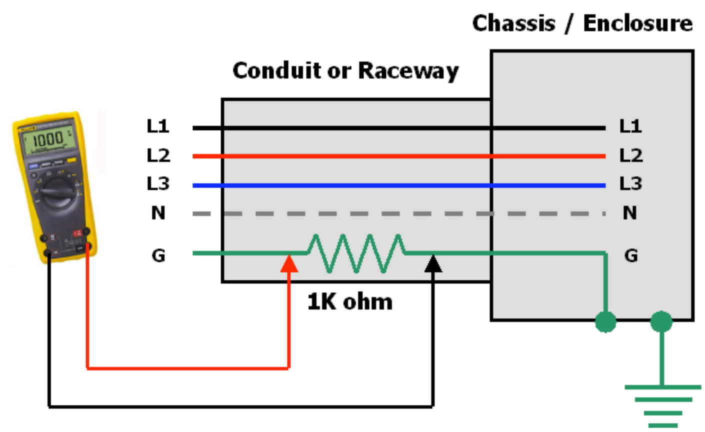


In the case of permanently installed or interconnected systems, which cannot be insulated from earth, leakage current measurements per NFPA-99 are not possible.

Alternate ground paths will always provide a lower impedance than the 1KΩ measurement resistance, so most of the leakage current will flow elsewhere.

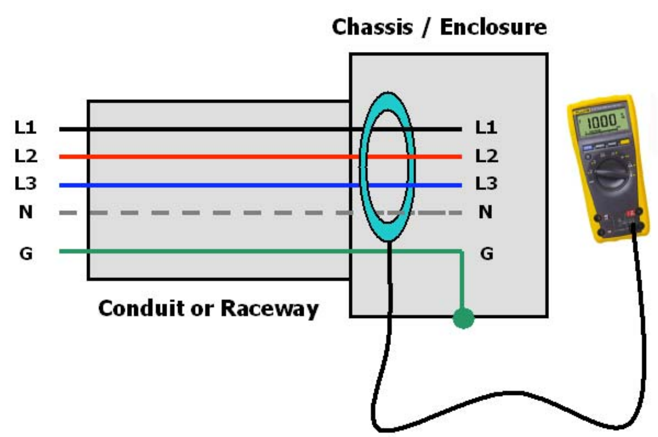
Alternately, ground currents flowing from other systems may be measured as leakage currents.

Even equipment insulated from earth will result in leakage-current measurement errors unless the ground impedance exceeds 100kΩ



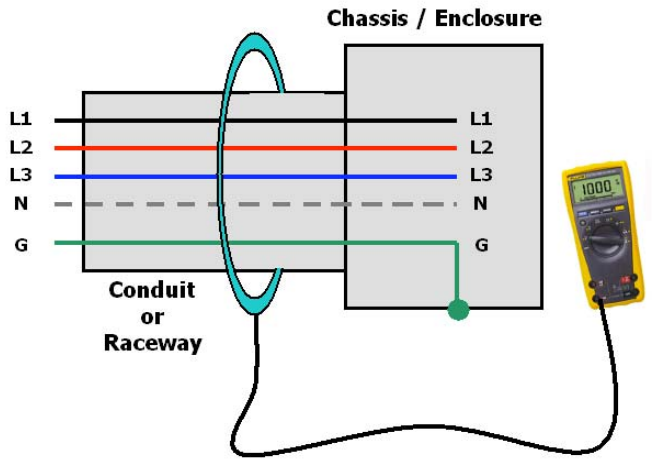
Provided that metering has adequate resolution and accuracy, and that the current probe can encircle all of the power conductors, leakage current measurements can be more accurately and reliably made this way for systems where insulation from ground is impossible or impractical.

Measurements are valid regardless of how many ground paths exist for the leakage currents to flow, and regardless of how much spurious ground current is present in the conduit or raceway.



Net Currents

In most electrical system, the sum of currents (Phase + Neutral + Ground) should be equal to 0 Amps. Any deviation from 0 can be considered a "Net Current". Measuring a net current involves clamping a current probe around all conductors in a circuit or feed.



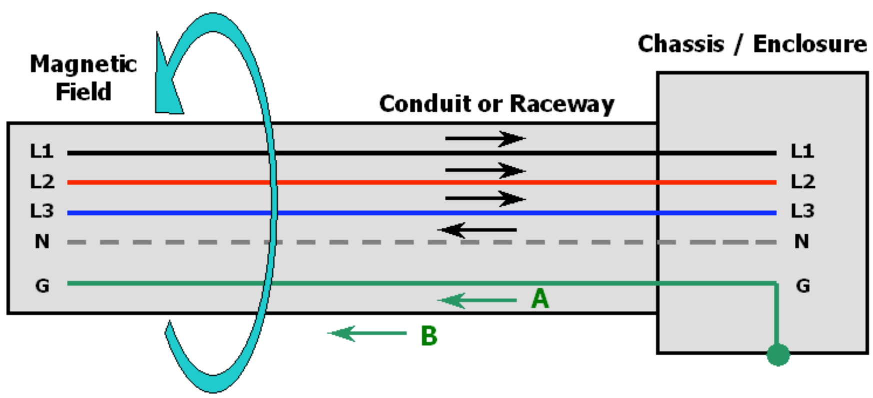
Net currents can have a number of causes.

1. Phase or Neutral currents that take different paths to the source (typical in a large office fluorescent light system, where neutrals are conjoined throughout the grid).
2. Ground currents that are injected into the circuit grounds via external sources.
3. Leakage currents that flow back to the source through alternate grounding paths, not through the circuit grounds.

The primary issue related to Net Currents is Extremely Low Frequency (ELF) magnetic fields. These fields are caused by any power frequency components (panels, transformers, etc) but the fields generated by normal electrical systems drop off quickly (within a few meters), with the cube of the distance from the source. Net currents, however, create a field that drops off much more slowly (related to the square of the distance from the source) – so that ELF magnetic fields related to net currents can cause problems 10's of meters from the source.

Net Currents are the sum of all phases, neutrals, and grounds (A) in a conduit or raceway, plus the conduit or raceway current (B).

Excessive net current can result in 60 Hz magnetic fields.

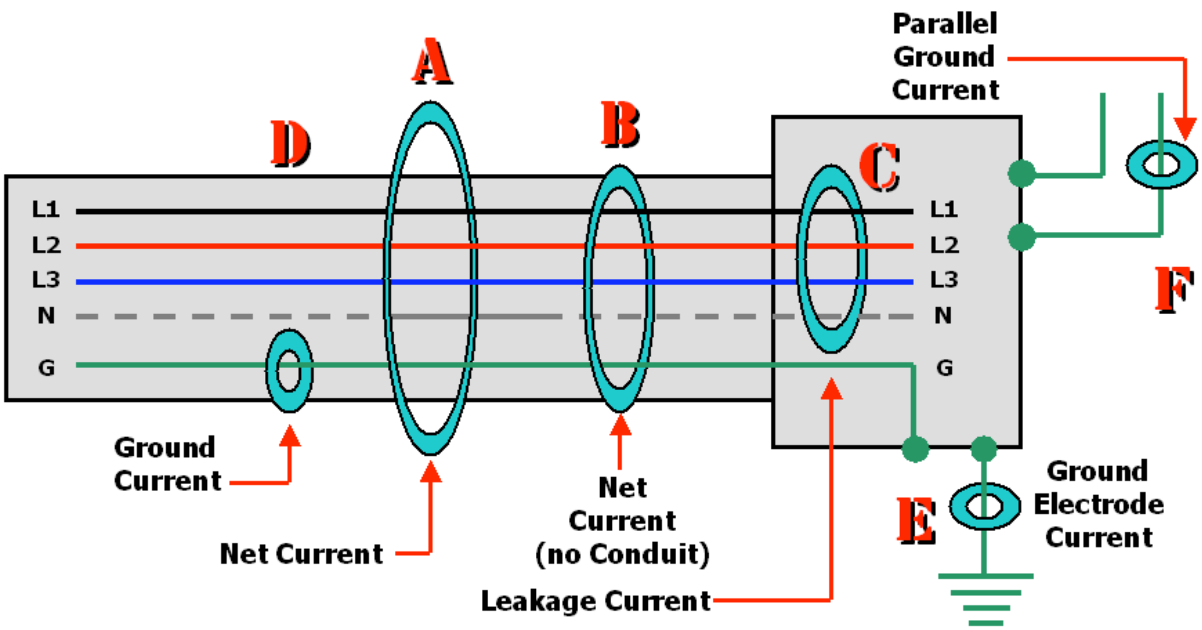


Tracking down Net Currents also involves thorough measurement of ground and leakage currents. If a conduit has a net current, one would need to look at the ground conductor current, the leakage current (Phases + Neutral), the entire conduit plus conductors, as well as the conductors without the conduit.

In many cases, net currents are related to connections with other electrical systems, so locating the places where the electrical systems are co-mingled, and separating these systems is often necessary.

Troubleshooting Techniques

Imagine a hypothetical site with high ground currents. On site measurements can help to identify the source of the ground currents, pointing to the possible cause, and also towards possible resolutions.



Net Currents

In the event of high 60 HZ (ELF) magnetic fields, checking the **Net Current** **A** can be simply done by measuring the current around the entire conduit or raceway. If net currents are low, magnetic fields are not related to net currents. By looping around various conduits, the culprit can be easily identified.

If Net Currents are high on a particular conduit or circuit, further study is warranted. Measuring the **Net Currents without the Conduit** **B** can be useful – if these are low, then the currents are flowing on the conduit.

Measuring the **Leakage Current** **C** can identify a phase or neutral current – if this is high, look for a co-mingled neutral and load currents taking an alternate neutral path back to the source. Switching off loads at the distribution panel can help to identify the exact circuit and location of the co-mingling.

Ground Currents

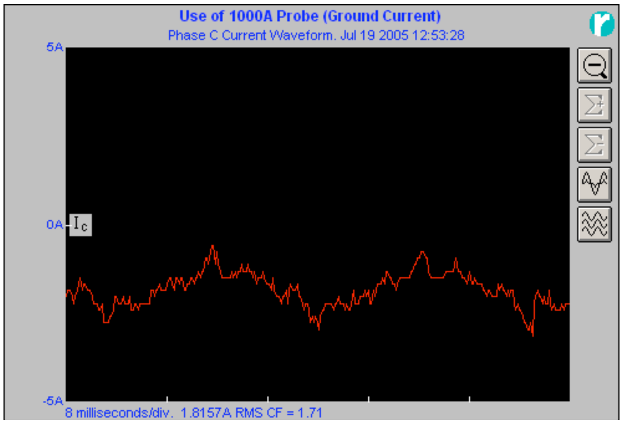
In the event of high **Ground Currents** **D,** check the **Leakage Current** **C**. If these are comparable, the ground is related to the leakage. Look for NG bonds, filters, or accidental current carrying connections to ground.

If they are not, the ground currents are related to external loops. Check the current on **Ground Electrodes** **E** and **Parallel Grounds** **F.** If these are low, the ground loop may be related to conduit, raceway, or mechanical connections.

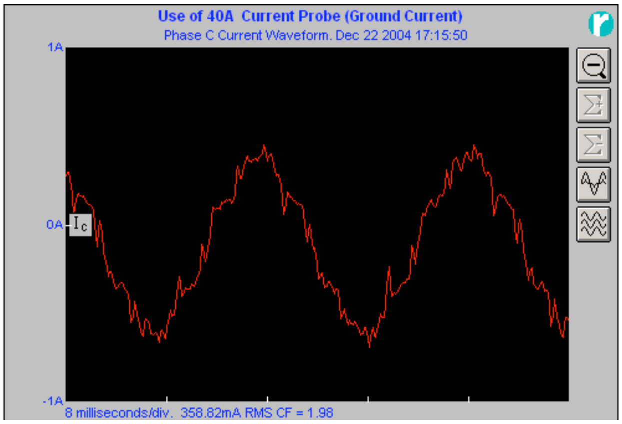
Instrumentation

While standard current clamps may be useful to measure low-level ground currents, in many cases, these tools are not optimal. The problems come in two main categories:

- Issues of resolution, accuracy, or DC offset when using higher amperage current probes



Measurement of ground currents with a high amperage current probe is often not diagnostic. Here, a 1000A current probe has a DC offset, making RMS and waveform measurements inaccurate.



Using a lower amperage current probe (40A, here) still has a small DC offset and some potential inaccuracy – but is much more accurate than the 1000A probe.

- Current measurement window in lower amperage current probes. Ground conductors may be full sized, or current measurements might be desired on ground rods, conduits, multiple conductors, etc.

The windows of current measurement clamps are typically sized based on the current to be measured – with a higher amperage rating corresponding to a wider measurement window.

Measurement of ground and leakage currents often requires both a larger cross-section measurement window, and a good measurement accuracy and resolution at low current levels.

In addition to resolution / accuracy issues and the cross-section of the measurement issue, the frequency response of the current probe can be important. It is often important to know the frequency of the problem currents, or to filter out high frequency / noise currents (for patient safety leakage current measurements, for example)

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In recent years, test equipment manufacturers have designed special meters, with low resolutions suitable for ground and leakage current measurements, and with a larger cross-section measurement window to enable measurement of oversized grounds, multiple conductors or mechanical ground paths such as bus bars, ground rods, or conduits.

Left

*The **Hioki Model 3283** is designed to measure leakage current, a special FILTER is useful to limit measurements to power system frequencies.*

Right

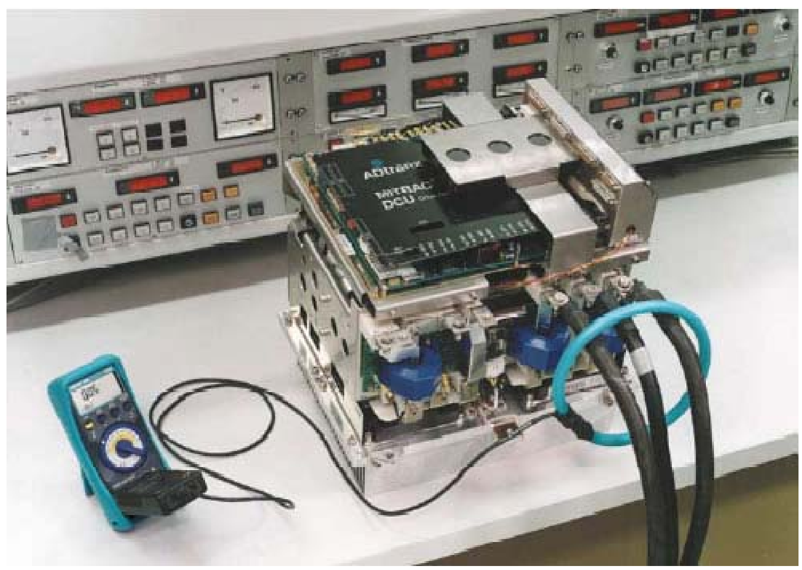
*The **AEMC Model 565** can measure to a resolution of 0.01 mA. The meter has a jaw capable of measuring 1" diameter conductors and devices.*

*LEM Instruments makes a flexible current probe in various lengths, with a 30A resolution. **(LEM-Flex)***

With this sort of device, current measurements on large conduits, mounting brackets, bus bars, and multiple conductors are possible.

At right, such a probe is used to measure leakage current on a large three-phase power feed.

Other manufacturers make similar probes.



In field tests, PowerLines has found the Leakage Current meters to be far more reliable and accurate than standard current probes for measuring low-level currents.

Extensive testing of the LEM-Flex devices have found them to be highly accurate regardless of orientation, deformation of the loop, or frequency of the current being measured (up to 10 KHz).