Simple system for locating ground loops

P. M. Bellan
Applied Physics, Caltech, Pasadena, California 91125

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A simple low-cost system for rapid identification of the cables causing ground loops in complex instrumentation configurations is described. The system consists of an exciter module that generates a 100 kHz ground loop current and a detector module that determines which cable conducts this test current. Both the exciter and detector are magnetically coupled to the ground circuit so there is no physical contact to the instrumentation system under test. © *2007 American Institute of Physics.*
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I. INTRODUCTION

Ground loops[1–7] cause spurious signals that interfere with the low-level signals typical of instrumentation and, in extreme situations, can damage equipment and endanger personnel. Ground loops are not only a problem in research laboratories but also in video and audio recording studios, in medical diagnostics, and in interconnected consumer audio/video systems.

Ground loops are especially hazardous in pulsed power systems because the large and rapidly changing stray magnetic fields in these systems can induce enormous transient voltages. In addition, ground loops in pulsed systems are notoriously hard to find because of the transient nature of the pulsed magnetic field.

Ground loops might be due to an accidental connection to ground (ground fault) or may be due to an inadvertent shortcoming of the system design. Locating ground loops is conventionally accomplished by disconnecting suspect cables until the ground loop disappears. This diagnostic method can be tedious if there are large numbers of cables and becomes impractical if more than one ground loop exists because in such a case disconnecting any single cable will not reveal the ground loop. In the situation of multiple ground loops, all cables would have to be removed and then reconnected one by one until a ground loop appears. Obviously, disconnecting large numbers of cables tends to disable equipment, making it difficult to simultaneously generate a ground loop and search for it. In complex situations the ground loop might never be found. Specialized permanently wired ground fault detection systems that continuously monitor ground currents in selected circuits have recently been developed[2,6,7] for use on large magnetic fusion research devices, but these systems are too complex, inflexible, and expensive to be practical in small-scale laboratory situations (e.g., for a sense of the complexity of the fusion device ground monitors see Fig. 1 of Ref. 2).

This article describes a system[8] that provides for rapid location of single or multiple ground loops. The system is noncontacting, does not require disconnecting any cables, and the equipment under test could in principle be powered on. The system is based on principles similar to those used in the fusion device ground fault detectors described in Refs. 2, 6, and 7 but differs by operating at a much higher frequency to reduce size and cost and by having a methodology for identifying which of a group of similar-looking cables is the one causing a ground loop. The system is sufficiently simple and inexpensive that it could be configured as a permanent addition to any electronic instrument to provide a warning whenever a ground loop becomes established.

II. CIRCUIT DESIGN

The ground loop location system consists of an exciter that generates a high frequency test current in the ground system and a detector which identifies which circuit is conducting this injected test current. The exciter (top, Fig. 1) is coupled to the circuit under test via a split-core ferrite current transformer. The detector (bottom, Fig. 1) is coupled to the circuit under test via an air-core Rogowski coil wound on a flexible plastic tube and having a large inside diameter so that it can be easily hand wrapped around a suspect cable or group of cables, as shown in the bottom left of Fig. 1. The Rogowski coil is based on the integral form of Ampere's law, i.e., $\oint_C \mathbf{B}\cdot d\mathbf{l}=\mu_0 I$ and so, provided the turns per length of the Rogowski coil uniform, the shape of the contour C does not matter. Thus, the Rogowski coil can be nonconcentric with linked cables, squeezed into tight locations, and deformed to be noncircular, all without changing the calibration or sensitivity. All that is required is that the Rogowski coil should link the test current. A Rogowski coil was used having 370 turns of No. 22 magnet wire wound with $N'=12.3$ turns/cm on 3/8 in. diameter flexible plastic tubing (radius $a=4.8$ mm) bent into a 10 cm diameter circle.

For a nominal $I\sim 30$ mA test current with frequency $\omega/2\pi=100$ kHz, the Rogowski coil provides a voltage $V_{\mathrm{Rog}}=N'\pi a^2\mu_0\omega I=2$ mV which is large enough for convenient use with low-cost operational amplifiers. The relatively high operating frequency of 100 kHz is used since the Rogowski coil voltage is proportional to ω [in contrast, the fusion device ground fault location systems were operated at much lower frequencies, e.g., $\omega/2\pi=0.5$ kHz,[6] 1.7 kHz,[2] or 3.3 kHz (Ref. 6)].

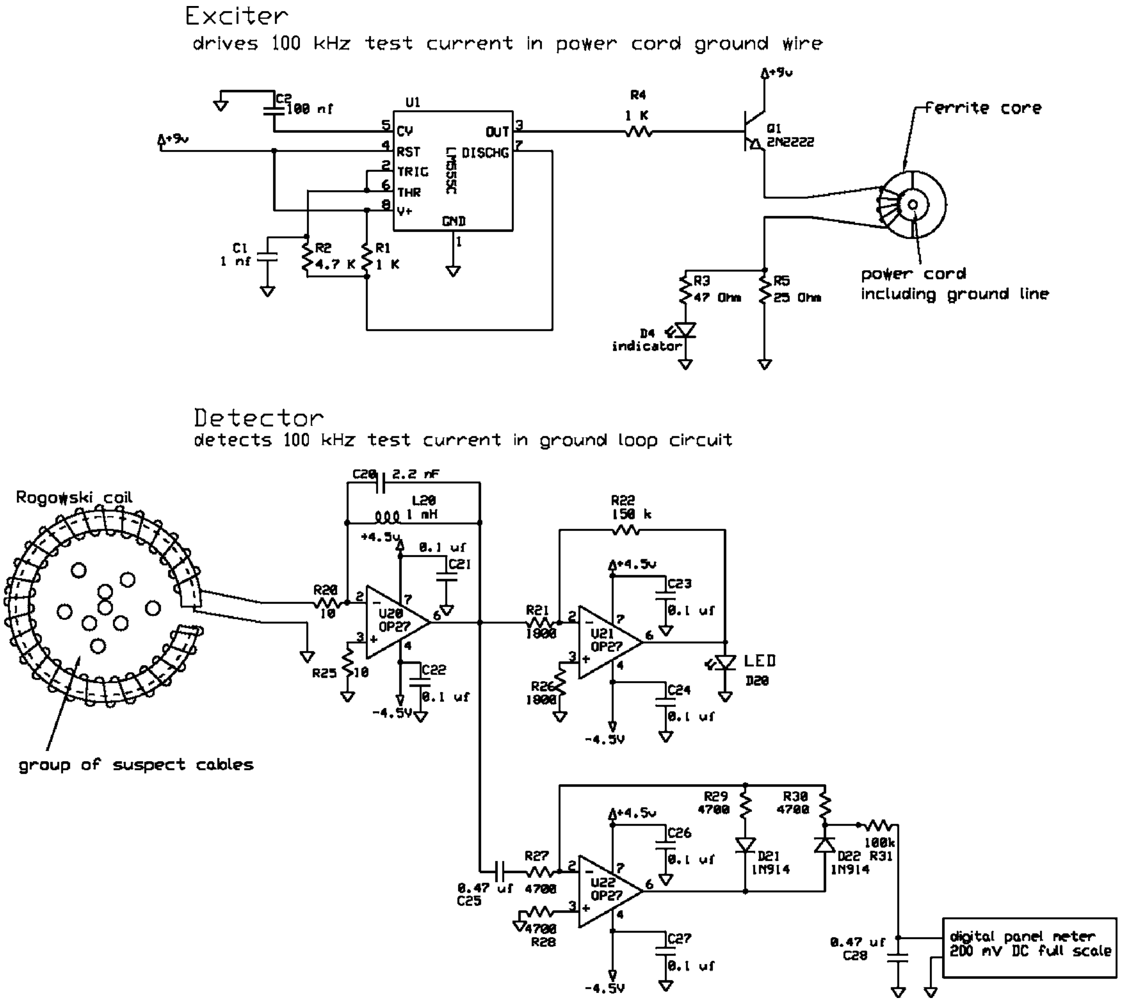

FIG. 1. Top: Exciter circuit. The power cable including ground wire of an instrument under test is threaded through the ferrite split core and so becomes the one-turn secondary of the ferrite current transformer. The exciter then drives a 100 kHz current through the ground wire if it is part of a complete circuit, i.e., part of a ground loop. Bottom: Detector circuit. The flexible Rogowski coil is hand wrapped around a suspect group of cables and if any of these cables carries the 100 kHz ground loop current generated by the exciter the detector LED illuminates. The meter gives a quantitative measure of the amplitude of this current which can be compared to the ground loop current measured at the exciter.

The weak coupling of the Rogowski coil as compared to a ferrite current transformer means that the Rogowski coil is effectively a nonperturbing probe of the test current. An amplifier tuned to the frequency $\omega/2\pi$ provides high sensitivity. The frequency $\omega/2\pi=100$ kHz is chosen as this is high enough to obtain an appreciable signal from the Rogowski coil, easily handled by low-cost operational amplifiers, but not so high that electromagnetic radiation fields become important. The physical flexibility of the Rogowski coil enables rapid and noncontact identification of a specific offending cable from a large set of cables having no obvious distinguishing visible features.

The exciter consists of a 555 function generator providing a 100 kHz square wave which then switches a 2N2222 transistor with emitter in series with the ferrite current transformer. The 8:1 turn ratio ferrite current transformer is wound on a Steward 28A4155-0A2 clamp-on split core in a plastic case which provides ease of attachment (a somewhat larger ferrite E-core was also used with similar results; because of the weak coupling the core properties are not critical). The current transformer has a $V_{1T}=0.7$ V one-turn loop voltage having the shape of a square wave with substantial droop and this voltage is not significantly altered when a ground loop is coupled. Different transformer turn ratios were tried and it was found that the detected signal became weaker for less than 8 turns, but higher than 8 turns made no difference. Because of the weak coupling, the ground loop can be considered as an impedance $R_{gl}+i\omega L_{gl}$ driven by the one-turn loop voltage so the current driven in the ground loop is simply $I=V_{1T}/(R_{gl}+i\omega L_{gl})$. The Rogowski coil voltage output then is $V_{Rog}=N'\pi a^2\mu_0\omega V_{1T}/(R_{gl}+i\omega L_{gl})$ which shows the benefit of operating at a frequency sufficiently high to have $\omega \gg R_{gl}/L_{gl}$.

The detector has a first-stage operational amplifier with a parallel LC feedback circuit tuned to give peak amplification at $\omega/2\pi=100$ kHz. The 10 Ω input impedance of the first-stage operational amplifier is so low that the system is essentially immune to electrostatic pickup, i.e., there is negligible capacitively coupled spurious electrostatic signal as would be the case for system with a high input impedance. This tuned first stage is followed by a second, untuned high-gain stage that drives a light-emitting diode (LED) indicator. Since the Rogowski coil only gives a signal when it links a current, the LED illuminates only if the Rogowski coil is wrapped around a wire conducting the 100 kHz test current.

A third operational amplifier is used to drive a digital voltmeter that provides an indication of the relative magnitude of the ground loop current. Because diodes have a nominal 300–400 mV drop, simple diode rectification of the 100 kHz ac signal does not result in a linearly proportional dc signal. In order to obtain a dc signal that is linearly proportional to the ac signal, two oppositely oriented 1N914 diodes are used in series with two 4.7 kΩ feedback resistors (see bottom of Fig. 1). Positive feedback current flows through one diode-resistor pair while negative feedback current flows through the other. Because the operational amplifier adjusts its output voltage to maintain a feedback current equal to its input current, the amplifier output voltage will assume whatever value is required to accommodate the diode voltage drop and so will not be linearly proportional to the input ac voltage. However, the feedback current is linearly proportional to the input voltage and input current. Thus, by measuring the voltage across one of the feedback resistors, a dc signal which is linearly proportional to the ac input is obtained. Because one end of the feedback resistor is at virtual ground, this measurement can be between true ground and the junction between the resistor and diode. The voltmeter indicates the relative severity of the ground loop and possible subdivision of the ground loop current into multiple paths.

III. SIGNAL ANALYSIS AND TESTING

We assume that the ground loop consists of the shield of RG-58 coaxial cable, a typical cable used in laboratories. The shield radius of RG-58 coaxial cable is 1.5 mm. Assuming the ground loop path length is between 1 and 20 m, the ground loop can be approximated as a torus with major radius R between 0.16 and 3 m and minor radius of $a=1.5$ mm. Since the inductance of a toroid is $L=\mu_0 R[\ln(8R/a)-2]$, typical ground loop inductances will be in the range 1 μH$<L<$30 μH. At $\omega/2\pi=100$ kHz, the inductive reactance of such ground loops will be in the range $0.6\ \Omega<\omega L<20\ \Omega$ which is much larger than the cable shield resistance so that the requirement $\omega \gg R_{gl}/L_{gl}$ is satisfied and the sensitivity is optimized.

As a first test, the shield of a 12 m long RG-58 coaxial cable was arranged in a rough oval on a laboratory floor and was measured to have ~14.6 μH inductance which is consistent with the 17 μH inductance predicted on the assumption that the cable is arranged in a circle rather than an oval. The cable dc resistance was 0.27 Ω. The exciter was coupled to the cable shield via the ferrite transformer and was able to drive ~36 mA through the cable shield loop as measured from the voltage drop across a 0.24 Ω shunt resistor in series with the cable shield loop. This corresponds to a reactive power $\langle IV\rangle=\tilde{I}\tilde{V}/2\simeq 0.7\times 0.036/2=12$ mW, about three orders of magnitude smaller than the power used in Ref. 2. If the Rogowski coil was also linked to the cable shield loop the LED illuminated. The LED extinguished if the cable shield loop continuity was broken.

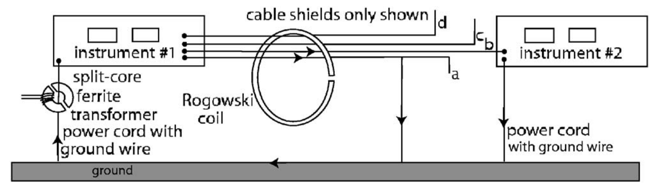

FIG. 2. Implementation: The split-core ferrite transformer induces a 100 kHz current, shown by arrows, in any ground loop or loops. The Rogowski coil detects this 100 kHz test current in any cable it links (i.e., cables “a” and “b” here). All circuits shown in the figure are ground circuits. The inductance of a typical ground loop is between 1 and 30 μH and the exciter-driven current in the ground loop is in the range between 20 and 300 mA. The detector LED illuminates when the Rogowski coil links a 100 kHz current larger than ~10 mA. The meter indicates what portion of the current driven by the exciter is being detected.

In order to determine the threshold sensitivity, the coaxial cable was slowly wound onto a 14 cm diameter cardboard tube while observing the LED. Winding the coaxial cable increases the inductance in the ground loop and so reduces the ground loop current. At a certain number of windings, the LED extinguished at which point the cable inductance was measured to be 55 μH. This indicates that the detector should be able to reveal ground loops in cable loops as long as 45 m which should be more than adequate for typical laboratory situations. If more sensitivity is required, the amplifier gain could be increased but this would require extra isolation between stages since the voltage gain at 100 kHz is already so high (~10^4 for the combination of tuned first stage and LED-driving second stage) that care was required in printed circuit board design to shield the stages from each other to prevent unstable feedback and oscillation.

IV. IMPLEMENTATION

The method for finding ground loops is sketched in Fig. 2. The exciter's ferrite split core is placed around the power cable of instrument No. 1. If a ground loop exists, the exciter induces a 100 kHz test current of the order of 30 mA in the ground line of instrument No. 1. The existence of a ground loop is established by wrapping the Rogowski coil around the instrument power cord as well. If the detector LED illuminates, there is a ground loop in the system, but at this stage the location (i.e., the identity of the cables comprising the ground loop circuit) is unknown.

Specific ground loops are then located by wrapping the Rogowski coil around groups of cables or individual cables connected to the instrument, as shown in Fig. 2. If the detector LED illuminates, then the wrapped cable or cables is part of a ground loop. Wrapping the Rogowski coil around cables “a,” “b,” “c,” and “d” causes the LED to illuminate and shows that at least one of these cables has a ground loop. If the Rogowski coil were wrapped around only cables ″c″ and ″d″ the LED would not illuminate, showing that cables ″c″ and ″d″ have no ground loop. Cable subgroups that do not illuminate the LED (i.e., ″c″ and ″d″ in this example) are then removed from the Rogowski coil. The procedure of removing cable subgroups is repeated until offending cables are isolated (e.g., cables ″a″ and ″b″ in Fig. 2). Absolute proof that a cable is offending is established when the LED is illuminated when the Rogowski coil is wrapped around that cable alone.

It was found in an actual laboratory situation that the identity of a single offending cable could be determined in about 2 min when this cable was one of a bundle of about 90 visibly indistinguishable cables. This contrasts with the conventional procedure of documenting how all cables in the bundle are connected, disconnecting them all, and then reconnecting them one by one until evidence of the ground loop reappeared in the instrumentation system. This conventional procedure would not just be tedious but might also be impractical because the system might become inoperable as cables are disconnected.

The detector and exciter could be left permanently linked to the instrument power cord so that the LED or some other suitable indicator would alarm whenever a ground loop was established. This exciter/detector system is simple and inexpensive enough that it could be permanently built into an instrument so that indication that a ground loop has been established could be displayed as a front-panel warning. The offending cable could then be determined using the method described in the previous paragraph.

If the instrument being tested is isolated from ground, a temporary wire can be connected from the chassis to ground and the exciter can then be used to drive the test current in this wire.

Accidental ground loops can be fixed by eliminating the unwanted short circuit to ground while intrinsic ground loops require a circuit redesign such as insertion of an isolation transformer or replacing the cable by an optical link.

V. MIGRATION OF GROUND LOOPS IN COMPLEX CIRCUITS

An interesting and unexpected aspect of ground loop elimination was discovered in the course of testing this system. It was found that eliminating an identified ground loop would cause the ground loop current to migrate (hop) to a new circuit path if such a path existed. This behavior means that eliminating ground loops will in general be an iterative process and explains why ground loop elimination is often quite frustrating.

The source of the ground loop is a mutual inductance between some external circuit and the ground circuit of a system; in the case of the test system discussed here the mutual inductance is provided by the ferrite transformer of the exciter circuit. This mutual inductance induces in the ground loop circuit a one-turn loop voltage V_{1T} which then drives currents in the ground loop. The drive voltage appears at the insertion point of the ferrite transformer and so one can imagine that a voltage source V_{1T} has been spliced into the ground loop circuit at the location of the ferrite transformer. Suppose as shown in Fig. 3 there is an impedance Z_0 due to the inductance and resistance of cable from the transformer location to some other location where the ground loop circuit divides into N parallel branches having respective impedances $Z_1, Z_2, Z_3, \ldots, Z_N$ such that $Z_0 \gg Z_1 \gg Z_2 \gg Z_3 \gg, \ldots, \gg Z_{N-1} \gg Z_N$ in approximate proportion to the cable lengths. Since $Z_0 \gg Z_1, Z_2, \ldots, Z_N$ the one-turn loop voltage V_{1T} and

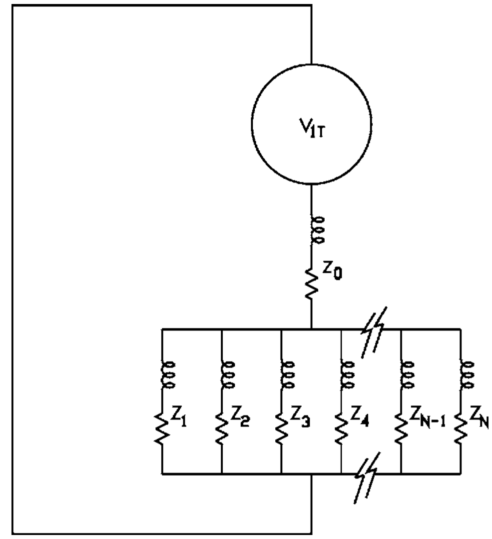

FIG. 3. Migration of ground loops: If $Z_0 \gg Z_1 \gg Z_2 \gg, \ldots, \gg Z_{N-1} \gg Z_N$ then ground loop current $I_{gl} \simeq V_{1T}/Z_0$ will initially flow through Z_0 and then mainly through Z_N. If Z_N is removed, the ground loop current I_{gl} will hop to flow mainly through Z_{N-1}. Thus, eliminating one ground loop circuit will simply cause the ground loop current I_{gl} to migrate to an alternate path if such a path is available.

impedance Z_0 act as a current source driving the ground loop current $I_{gl} \simeq V_{1T}/Z_0$ through the paralleled impedances $Z_1, \ldots, Z_N$. Because $Z_N \ll Z_{N-1} \ll Z_{N-2}$, etc., nearly all this current I_{gl} will flow through Z_N. However, if the path through Z_N is identified and then eliminated, this current will redirect to flow through Z_{N-1} which will now be the highest conductance path. Thus, eliminating the Z_N ground path causes the ground loop current I_{gl} to hop to the Z_{N-1} path. In turn, eliminating the Z_{N-1} path will cause the ground loop current to hop to the Z_{N-2} path.

Hence, eliminating one ground loop path can effectively create another. Because a new path may be obvious only after being energized, it is necessary to identify and eliminate observed ground loops and then check whether this has created new ground loops. The new ground loops are then identified and eliminated and the process continued until I_{gl} becomes zero. Using the meter to measure the ground loop current at the exciter and then the extent to which this current becomes subdivided into ground loop subcircuits indicates the extent to which such a path-to-path migration of ground loop currents can occur. As the ground loops are eliminated, the load impedance increases so the ground loop current will decrease, but if $Z_0 \gg Z_1, Z_2, \ldots, Z_N$ there will be little difference between $V_{1T}/(Z_0+Z_{N-m})$ and $V_{1T}/(Z_0+Z_{N-m+1})$ so the reduction in ground loop current might be negligible until all N ground loop paths are found and eliminated.

ACKNOWLEDGMENTS

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