Ground Loops: The Rest of the Story

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ABSTRACT

The mechanisms that enable so-called ground loops to cause well-known hum, buzz, and other audio system noise problems are well known. But what causes power-line related currents to flow in signal cables in the first place? This paper explains how magnetic induction in ordinary premises AC wiring creates the small voltage differences normally found among system ground connections, even if “isolated” or “technical” grounding is used. The theoretical basis is explored, experimental data shown, and an actual case history related. Little has been written about this “elephant in the room” topic in engineering literature and apparently none in the context of audio or video systems. It is shown that simply twisting L-N pairs in the premises wiring can profoundly reduce system noise problems.

1. BACKGROUND

Severe noise problems such as hum or buzz often arise in audio and video systems that are in perfect compliance with National Electrical Code (NEC) and industry practices. Other systems remain trouble-free in spite of code violations, floating grounds, and other problems. Subtle factors that are rarely under the control of the system designer or installer include accidental connections to the grounding system, unknown "fixes" to building wiring, and badly designed equipment. These unknowns may conspire to make it appear that luck is a major factor, but the vast majority of noise problems are caused (or made far worse) by small ground voltage differences between the individual pieces of equipment that make up the system. Previous papers, such as Whitlock’s *"Balanced Lines in Audio - Fact, Fiction, and Transformers"* [1], analyze the effects of balanced line drivers, cables, and line receivers on the rejection of this ground noise. Of course, the inherent susceptibility of unbalanced interfaces to incredibly small ground voltage differences is well known.

The authors have found explanations of the sources of these ground voltage differences in the literature quite unsatisfactory. The most common is that they are voltage drops in the safety ground wiring due to the flow of accumulated equipment leakage currents. However, even in the worst case scenario, leakage currents can’t account for the much higher voltage differences observed in the field. In 2001, this failing of traditional explanations prompted Whitlock to postulate that the cause must be magnetic induction effects in the premises wiring itself - since the physical arrangement of current-carrying and safety ground conductors in conduit essentially creates a long, thin, single-turn transformer. In 2002, Whitlock performed some basic laboratory experiments to confirm the theory and began including the explanation in his seminars and lectures in 2003. [2][3] In 2007, he did a small-scale demonstration of the mechanism. [4] Since then, a number of confirming experiments have been performed by others, although none were judged sufficiently rigorous to allow correlation to engineering theory. [5][6] In recent years, this parasitic transformer is often referred to as the “conduit transformer.”

2. THEORY

Michael Faraday (1791-1867) is perhaps the greatest experimental scientist who ever lived. In 1839, he demonstrated that electromagnetic forces move electrons. He effectively invented the transformer and electric motor and was renowned for explaining concepts in simple terms (we really like this guy!). His theories demonstrate electromagnetism as a fundamental force of nature. “Faraday explained electromagnetic induction using a concept he called lines of force. However, scientists at the time widely rejected his theoretical ideas, mainly because they were not formulated mathematically. An exception was Maxwell, who used Faraday's ideas as the basis of his quantitative electromagnetic theory.” [7][8]

Basically, Faraday’s law says that:

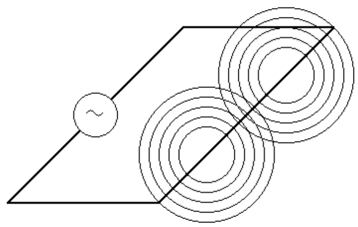


Figure 1: A conductor carrying AC current will be surrounded by a changing magnetic field

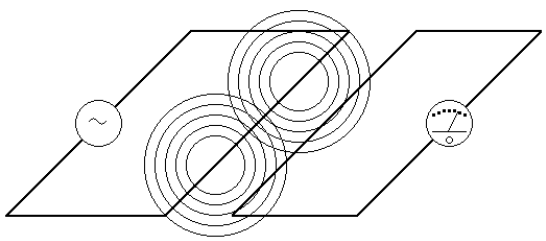


Figure 2: A voltage will be induced in a conductor exposed to a changing magnetic field, proportional to the magnetic field’s rate of change

In premises AC power wiring, each of the load conductors (i.e., “line” and “neutral”) normally carry equal currents but in opposite directions at any instant in time. This causes the magnetic fields surrounding each to point in opposite directions but have equal strength, since the polarity of each field is determined by the direction of current flow and the strength (magnitude) of the field is directly proportional to current. This not only causes the conductors to repel each other but it results in a plane of zero magnetic flux exactly midway between them. Consequently, if a third conductor (i.e., safety ground) is positioned along this “zero-flux” plane, no voltage will be induced into it. However, if the safety ground conductor is slightly nearer the “line” or “neutral” conductor, a voltage will be magnetically induced over its length. This voltage is directly proportional to the length of wiring run and, perhaps most importantly, directly proportional to the rate of change of the load current in “line” and “neutral.”

2.1 The Equations

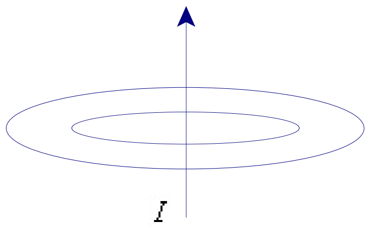
The underlying theory and associated equations are shown on pages 3 and 4.

3. THE EXPERIMENTS

The goal of the experiments was two-fold. First, we wanted to create a carefully-controlled “reference” setup that might confirm the predictions of theoretical equations. Second, we wanted to compare several widely-used conductor configurations used in premises AC power wiring over a frequency range that simulate harmonic currents drawn by equipment power supplies.

3.1 The Test Setup

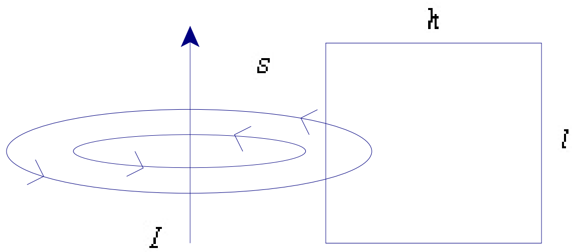
A block schematic of the test setup is shown in **Figure 3**. The 6.1 m (20 foot) wiring sample was suspended 0.76 m (30 inches) above the floor on four all-plastic “sawhorses” and the return loop exited the test sample perpendicularly to the return wire taped to the floor directly beneath and parallel to the sample. Current was delivered to one end of the sample with approximately 1 m (39 inches) of hand-twisted star-quad cable to assure that its magnetic contribution was negligible. The signal generator was a Hewlett-Packard 209A which drove both channels of a Boulder 500 audio power amplifier rated at 250 W per channel into 8 Ω. Two 8 Ω, 250 W resistors served as dummy loads and their currents were summed into the test sample, as shown in Figure 3. Using a Hioki 3283 high-sensitivity clamp-on ammeter, actual test current was monitored, and generator level adjusted, to maintain a constant 6.00 A rms current as the generator frequency was varied. Induced voltage was measured with a Fluke 187 true-rms multi-meter through a selectable single-pole low-pass filter having a −3 dB frequency of either 55 kHz or 5 kHz. A miniature coaxial cable connected the loop to the filter and meter to avoid magnetic pickup in the cable. The filters were used to eliminate interference from a nearby AM radio transmitter. The multi-meter residual reading (noise floor), with all test equipment powered but signal generator output shorted, was about 20 µV rms. A prime consideration for this relatively large-scale experiment was to eliminate as many potential sources of error as possible. A survey of the experiment area showed that ambient magnetic fields were well under 0.3 milli-gauss as measured with a sensitive triaxial gauss meter. [9] *(continued on page 5)*



(Main Text Continues on Page 6)

The magnetic field due to an infinitely long current-carrying wire at distance r is: $B = \dfrac{u_o I}{2\pi r}$

The total magnetic flux passing through the loop is obtained by summing all the magnetic field over the area of the loop. Keep in mind the total magnetic flux through the loop is the flux that passes perpendicular to the loop.



$$\Phi_B = \int d\Phi_B = \int \vec{B} \cdot d\vec{A} = \frac{u_o I l}{2\pi} \int_s^{s+h} \frac{dr}{r} = \frac{u_o I l}{2\pi} \ln\left(\frac{s+h}{s}\right)$$

According to Faraday's law the induced emf (voltage) is:

$$\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\left[\frac{u_o I l}{2\pi} \ln\left(\frac{s+h}{s}\right)\right] = -\frac{u_o l}{2\pi} \ln\left(\frac{s+h}{s}\right) \cdot \frac{dI}{dt} = -\frac{u_o l b}{2\pi} \ln\left(\frac{s+h}{s}\right)$$

where: $\dfrac{dI}{dt} = b$

If the current flowing in the wire is a sine wave, $I = \sin(wt)$, then the derivative is:

$$\frac{dI}{dt} = \frac{\sin(wt)}{dt} = w\cos(wt)$$

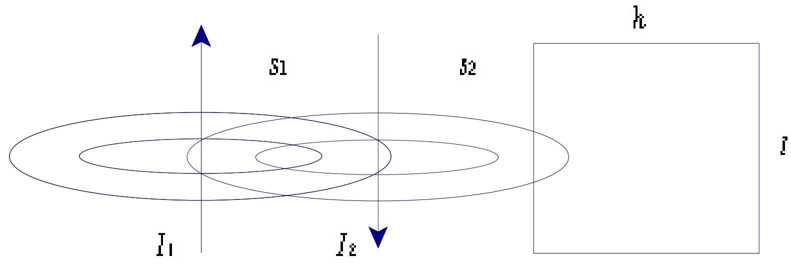
where $w = 2\pi \cdot f$

Note that the magnitude of the induced emf (voltage) is directly proportional to frequency:

$$\varepsilon = -\frac{u_o l}{2\pi} \ln\left(\frac{s+h}{s}\right) \cdot \frac{dI}{dt} = -u_o l f \cos(2\pi f) \ln\left(\frac{s+h}{s}\right)$$

If another current carrying wire is located in proximity of the loop with opposite direction, we can subtract the contribution from this wire using the same equation with different distance values. This property is called superposition.

$$\varepsilon_{tot} = \varepsilon_2 - \varepsilon_1 = -\frac{u_o l}{2\pi}\left[\ln\left(\frac{s_1+h}{s_1}\right)\frac{dI_1}{dt} - \ln\left(\frac{s_2+h}{s_2}\right)\frac{dI_2}{dt}\right]$$



If currents I_1 and I_2 have equal magnitude and opposite direction, and we apply the magnetic permeability of free space $u_o = 4\pi \cdot 10^7$, the formula reduces to:

$$\boxed{\left|\varepsilon_{loop}\right| = \left|\varepsilon_2 - \varepsilon_1\right| = -4\pi \times 10^{-7}\, lfI\left[\ln\left(\frac{s_1 + h}{s_1}\right) - \ln\left(\frac{s_2 + h}{s_2}\right)\right]}$$

For example, to calculate the induced voltage at 1 kHz for the "Ref" test setup:

Loop length: $l = 240"(6.096m)$

Loop width: $h = 30"(0.762m)$

Distance from wire 1 to loop: $s_1 = 0.7"(0.01778m)$

Distance from wire 2 to loop: $s_2 = 0.5"(0.0127m)$

Current: $I_2 = I_2 = 6A$

Frequency: $f = 1{,}000\ Hz$

$$\left|\varepsilon_{loop}\right| = \left|\varepsilon_1 - \varepsilon_2\right| = (4\pi \times 10^{-7})(6.096)(1{,}000)(6)\left[\ln(43.85) - \ln(61)\right] = 15mV$$

We compared our experiment measurements to values predicted by the equation at various frequencies. We were quite gratified to find they agreed within ±5%:

Frequency	**Loop EMF (measured)**	**Loop EMF (predicted)**
1 kHz	15 mV	15 mV
2 kHz	34 mV	31 mV
5 kHz	81 mV	76 mV
10 kHz	**163 mV**	**153 mV**

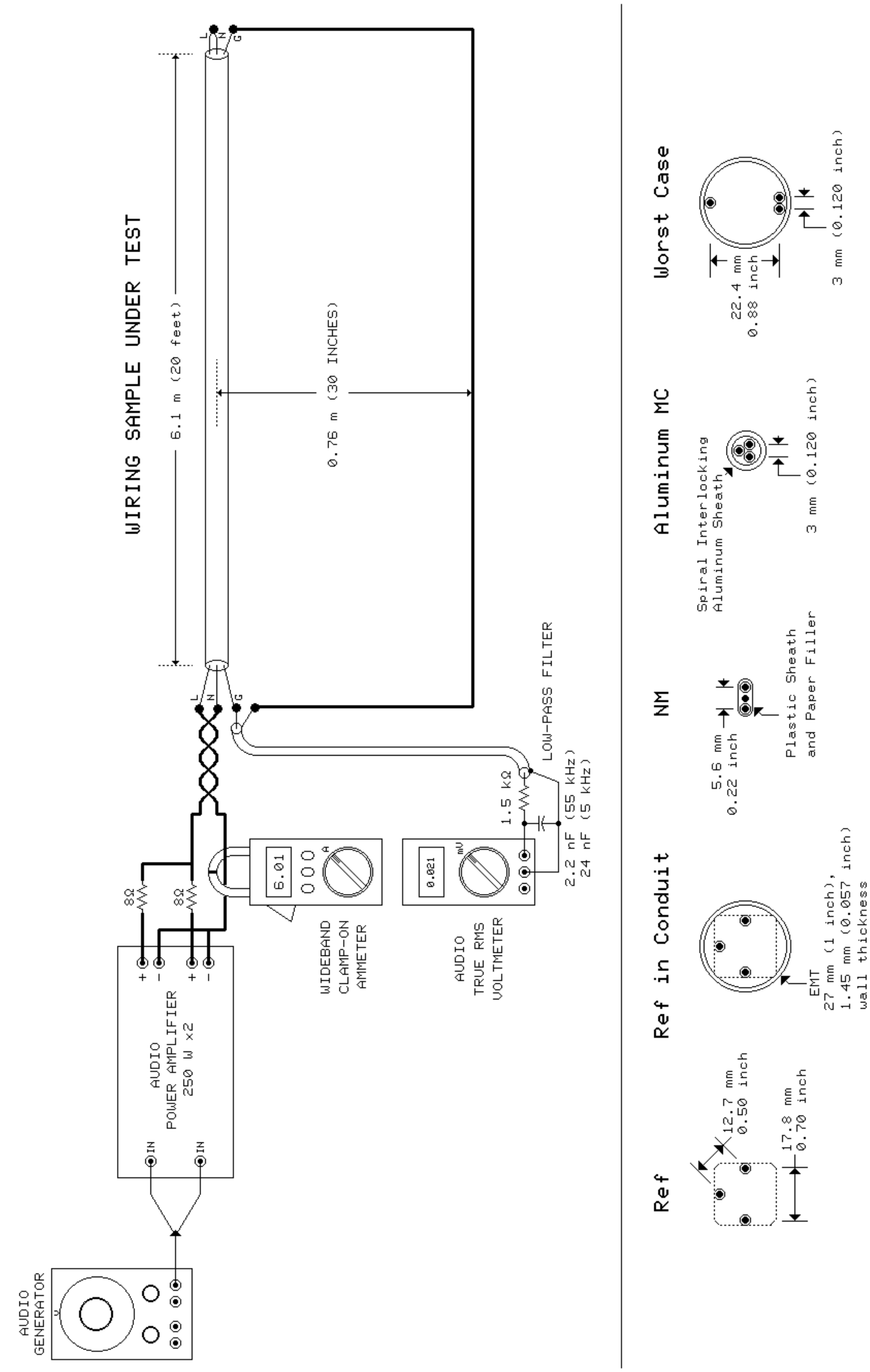


Figure 3: The Reference Test Setup

A preliminary test confirmed that the return path of the pickup loop was far enough from the test sample to avoid significant error due to magnetic pickup in the return path. The test sample was lowered to half its height, to 0.38 m (15 inches), and no detectable change in output voltage was observed. The response of all instruments was checked over the frequency range used, including the RFI filters, and appropriate correction factors were applied. It should be noted that, over the 50 Hz to 2 kHz frequency range, no corrections were necessary.

3.2 Test Samples and Data

The “Ref” test sample consisted of #12 AWG solid type THHN copper wires embedded in milled grooves on three sides of a 6.1 m (20 feet) long piece of 19 mm (0.75 inch) square hardwood. As shown in Figure 3, this placed the wires in a triangular array with wire-to-wire spacings of 17.8 mm (0.70 inch) and 12.7 mm (0.50 inch) at their centers. With respect to the ground wire, the current-carrying wires were on opposite and adjacent sides of the square. As explained at the end of the “The Equations” section, there was excellent agreement between theory and measured data for this reference sample.

Other test samples also used #12 AWG (2 mm) solid copper conductors. Only the “Worst Case” plot was calculated rather than measured. It assumes that the ground wire is a close as possible, 3 mm (0.120 inch), to one of the current-carrying wires and as far as possible, 22.4 mm (0.88 inch), from the other in trade-size 1-inch (27 mm) electrical metallic tubing (EMT).

The “Twisted L-N” data is for a sample in which line and neutral conductors were twisted at about five twists per foot. The twisted-pair and a straight ground wire, shown in Figure 4, were then placed in a 6.1 m (20-foot) section of trade-size 1-inch (27 mm) plastic (PVC) conduit. No attempt was made to optimize positioning of these wires.

Figure 4: Close-up of “L-N Twisted” Sample

All the measured data is summarized in graphical form in **Figure 6**. The configuration shown in Figure 4 above seems to offer the lowest ground voltage induction of any tested - the “Worst Case” is over 1,000 times worse!

4. FIELD EXPERIENCE

One of the most often-heard AV system noise complaints is about inexpensive, phase-control light dimmers. Since voltage induced into the safety ground is proportional to the rate of change of load current, it makes perfect sense that these light dimmers have a bad reputation for creating terrible audio system noise. The highest induced voltage will be produced when the dimmer is set at approximately 50% brightness. Figures 5 and 6 show the current in six 100-watt incandescent lamps controlled by a typical low-

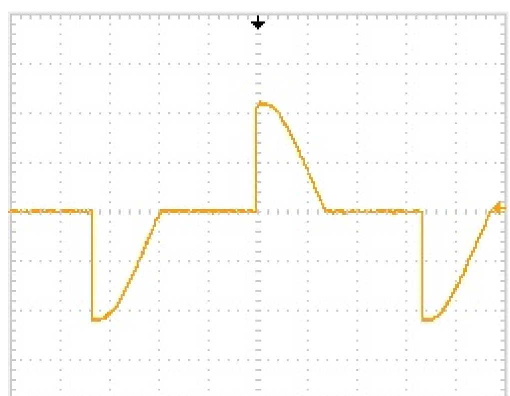


Figure 5: Dimmed Lamp Current
4 A/div vertical, 2.5 ms/div horizontal

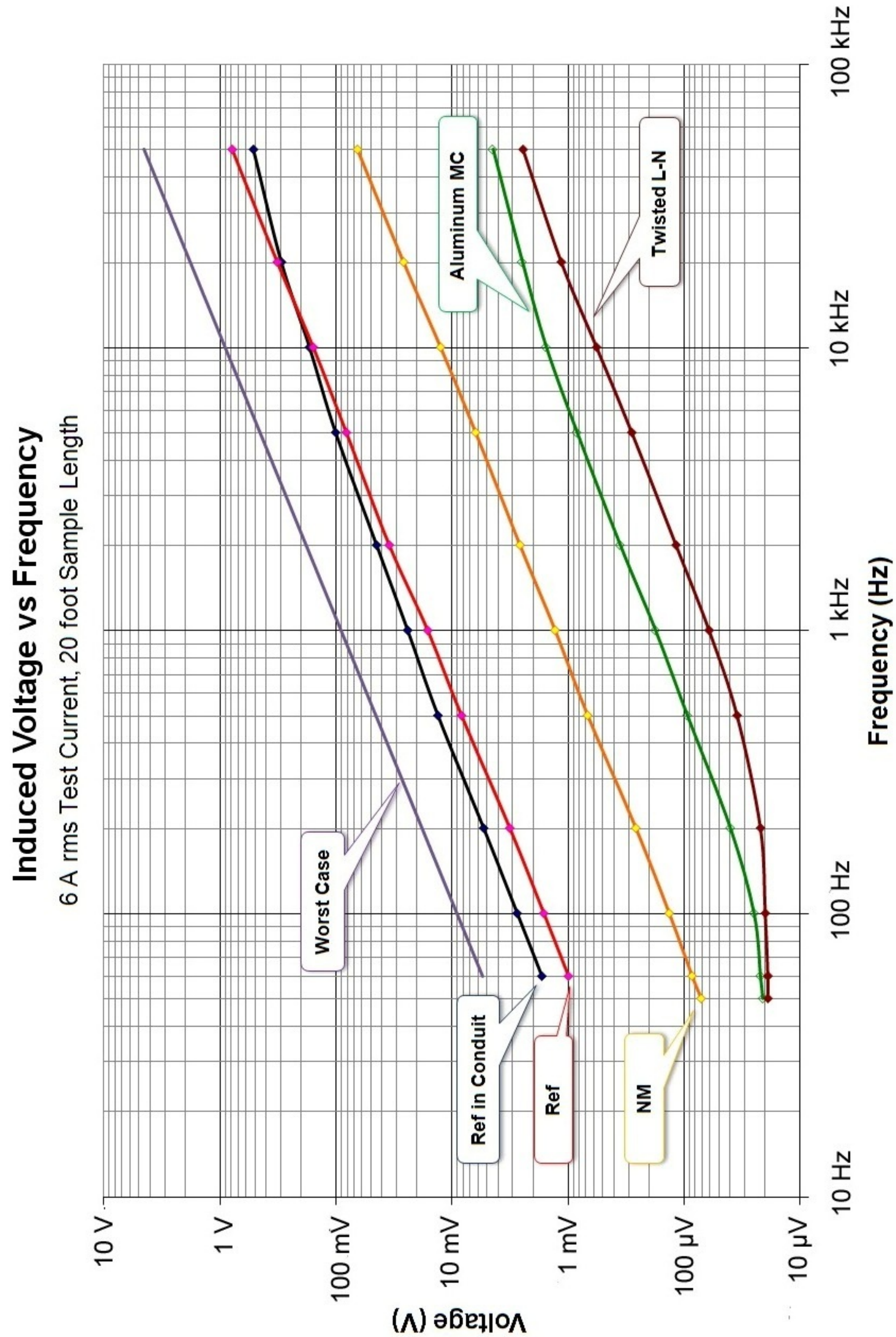


Figure 6: Plots of the Experimental Measurements

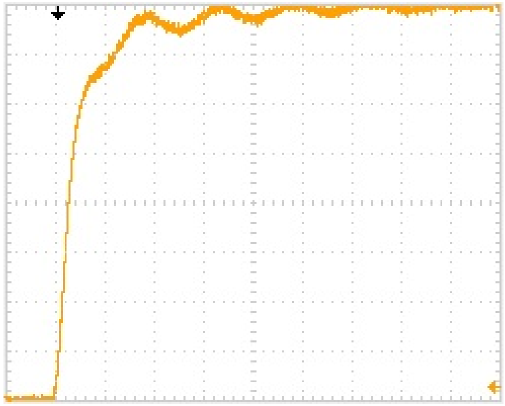


Figure 6: Dimmed Lamp Current
1.1 A/div vertical, 5 µs/div horizontal

cost 120-volt, 600-watt dimmer (Lutron S-600H) when it is set at about 50% (a worst-case for noise induction). Note that the current switches very quickly, exhibiting a 10% to 90% rise-time of only about 5 micro-seconds!

Most pieces of electronic equipment, even those with “brute-force” power supplies that draw high peak currents only at the peaks of the AC sine wave, do not have such fast current rise-times. The ground voltage difference shown in Figure 7 is typical of the induced ground voltage in many large systems. The feeder powers about a dozen audio power amplifiers.

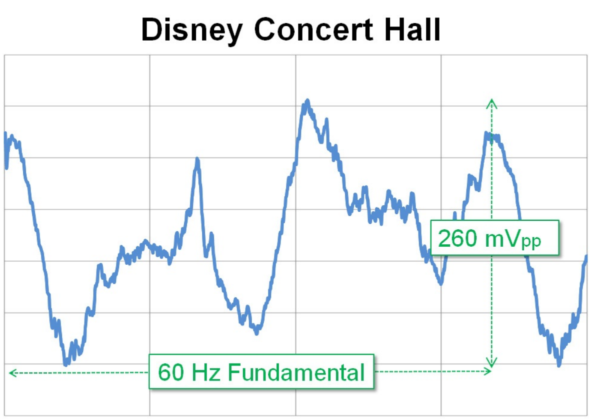


Figure 7: Isolated Ground Voltage between Amplifier Room and Main Electrical Room (200' feeder)
50 mV/div vertical, 5 ms/div horizontal

A few years ago, Whitlock was asked to help find a long-standing buzz problem in an auditorium sound system at Seahawk Stadium in Seattle. In the auditorium were two suspended 12 kW powered speaker clusters. The power was 208-volt 3-phase. Power wiring connecting the two clusters consisted of five wires: three phase wires, a neutral wire, and a (safety) ground wire. These individual wires were laid in an overhead channel. Current in each of the phase wires was measured at about 30 A rms with the amplifiers idling. Customary checks confirmed that there were no inadvertent connections between safety ground and building steel at the clusters. Audio was routed to each cluster via a single cable and XLR connector from the performer’s mixing console. It was reported that a buzz contaminated the same channel regardless of what make and model mixer was used. A ground voltage difference, as measured between shield pins of the cables from the two clusters, was measured at about 650 mV rms.

On the hunch that this voltage difference was due to magnetic induction in the power interconnect wiring, I asked the staff to twist, as tightly as possible, all the current-carrying wires (3 phases and neutral) and lay the safety ground wire next to the bundle a few inches away. After this was done, the voltage between shield pins of the two cluster inputs had dropped to less than 3 mV rms (near residual for the meter used at the time). Connecting a test signal source confirmed that the buzz was gone!

5. CONCLUSIONS

The trend in modern audio systems is toward increasing dynamic range, which dictates that noise artifacts such as hum and buzz must be kept to an absolute minimum. The effects of uncontrolled geometry in premises wiring are unpredictable degrees of “ground loop” problems, often making it appear that luck is responsible. This paper has shown how simply twisting the current-carrying wires in premises AC power wiring can have an astonishing impact on real-world audio system dynamic range. It should be emphasized that the current-carrying conductors for ***every*** branch circuit in a given conduit must be twisted to avoid magnetic induction into any of the ground wires in that conduit.

Other steps that can help minimize system noise:

- Avoid unbalanced signal interconnections (generally found in consumer or musical-instrument equipment)
- Avoid professional equipment that has the “pin 1 problem” [10]
- Confirm that professional equipment balanced

inputs have adequate common-mode noise rejection in real-world settings [11]
- Confirm that there are no Code-violating neutral to safety ground connections in the premises wiring [12]
- Check every AC outlet for proper wiring - especially for neutral-ground reversals [12]

ACKNOWLEDGMENTS

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