Appendix B: AC Power Non-linearity, Harmonics, Points of Reference, and Wiring-error Identification Tracing and Correction Protocol

There are two fundamental phenomena in Alternating power systems that are of interest. The first is a **Transient**. These are momentary perturbations of the Alternating Power System's Sine Wave and any related field, and occur whenever something is turned on or off. These transients can propagate (and be detected) for miles within interconnected systems. That is, in systems such as WYE, anyone turning a lamp on / off will produce an instantaneous transient electrical change that will propagate through the power source to all interconnected branches of the circuit. Since the electric distribution in each residence can be thought of as two hands (the buses) with many fingers (the circuits), anytime a switch is operated in any of the circuits, all circuits associated with a bus will experience the transient directly. To illustrate the point, when the refrigerator turns on, the lights on that bus will momentarily dim substantially, and remain dimmer to a lesser extent until it turns off.

Each transient will produce the second phenomenon of interest, a broad but momentary spectrum of **Harmonics**, or multiples of a fundamental frequency required to produce the step change in voltage / current. A simple and tangible display of this is provided with lightning, in that each stroke of non-alternating current will blanket the frequency spectrum, producing electric static through all frequencies from zero Hertz to the Megahertz MHz region, blanketing all AM radio frequencies.

Unfortunately, some devices produce these transients for each pulse of energy, or twice per cycle (120 transients per second). Thus <u>if 180 or 300 Hertz (Hz) is produced by a switching condition, and it occurs 120 times per second, the 180 / 300 Hz is also available 120 times per second, which may be considered a continuous presence</u>. This can be compared to a bird chirping a note intermittently, and then somehow doing it so frequently that it appears to be a constant tone. Some of these devices are fluorescent lighting of any type, dimmer switches, and switching power supplies. When such devices are energized, they will produce many harmonics easily detectable with an AM radio. Another telltale indicator is that the label on most of these devices depicts any input as acceptable between 90 to 250 V. **Since the current used by these devices does not resemble the applied voltage, the device is designated as non-linear**.

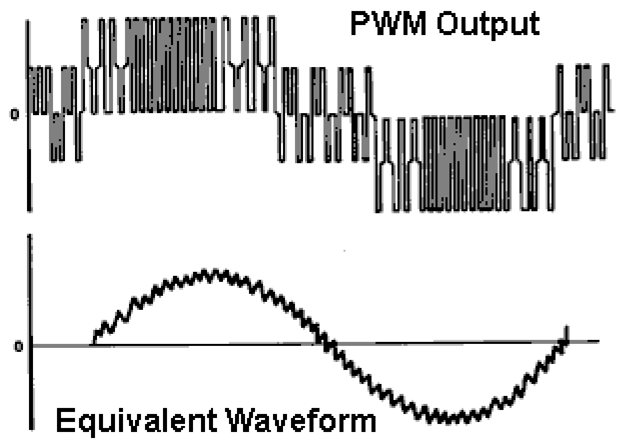
Electricity can have plenty of non-linearity, based on how the voltage available is allowed to produce current, and productive work. Non-linearity occurs when anything is powered, and whose response to applied voltage is anything other than that of a hot wire.

Since most individuals on this planet who have electricity also have non-linear loads, most of those individuals also contribute to the non-linear mix that eventually may find itself routed to undesired places.

When we look at the power we use, when it involves a hot wire (incandescent lamp, toaster, etc.) the current produced is an exact replica of, and synchronized with, the applied voltage. On a meter it would be a number, on an Oscilloscope it would have a shape similar to lazy S (~), and on a Spectrum Analyzer it would be a single vertical marker on a vast universe of frequencies that we commonly call the Electromagnetic Frequency Spectrum.

When the power is used by anything other than a hot wire (fluorescent lamp, dimmers, digitals, VFD, PWM, etc.) the resulting current no longer looks like the voltage used to produce it. On a meter it would be a number (but some meters are now dramatically affected by the many frequencies required to produce that shape), on an Oscilloscope it might look like a peak, triangle, etc., and on a Spectrum Analyzer it would look like a choir of many frequencies decreasing in size as the frequency increases.

When the generation of power is associated with wind turbines there are some additional and unusual problems. Primarily there is the link-up to the power system when they begin to generate power, and similarly when they go offline due to lack of wind. Since the blades vary their speed with the wind, and they move at extremely low speeds, the speed must be increased by a gearbox or transmission, which has a fixed gear ratio. This presents a problem, because the generator's rotational speed varies, but the electrical system interconnection frequency does not. One way around this is by a PWM VFD. That is, a Pulsed Width Modulated Variable Frequency Drive. These devices produce very steep electrical changes (or transients, that produce lots of harmonics) to eventually produce a "smooth" voltage to be fed to the generator for excitation, as depicted in the sketch below. Unfortunately these very steep electrical changes Induce voltages and currents in the rotor that cause electric discharge machining (EDM) between the bearings and the races they fit into, causing pitting of the races. This can make the generator fail in as little as six months. An elegant solution to eliminate the induction is to short out these voltages and currents with an electrically conducting collar around the generator's shaft. However, this elegant solution shorts out the voltages and current to ground, and remembering that the various ground connections have instantaneously different voltages, some of the current flows through the soil between the different grounds, which is also known as **Stray Current**.



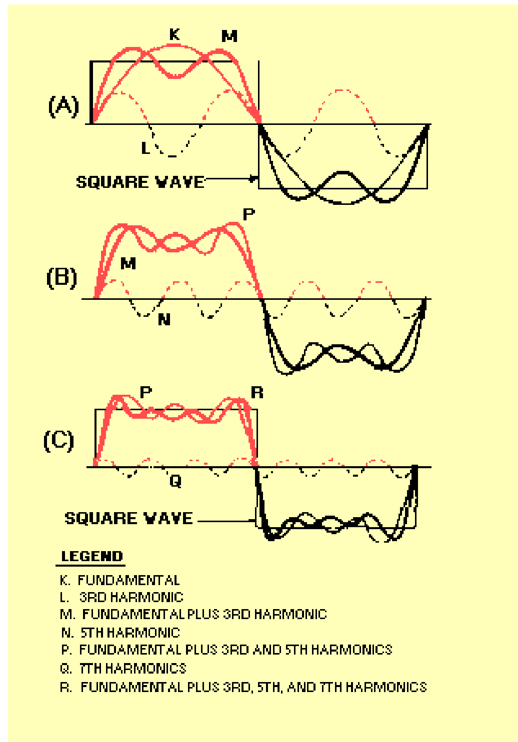
PWM VFDs are Switch-mode Power Supplies, and they produce steep waveforms to produce the desired output. The steepness of the changes varies the harmonics presence, in that the steeper the waveform, the broader the frequency span of the harmonics required to produce the waveform.

COMPOSITION OF NONSINUSOIDAL WAVES – Excerpted from: NEETS (Navy Electrical and Electronics Training System) Module 9 – Wave Generation and Wave Shaping circuits

Pure sine waves are basic wave shapes from which other wave shapes can be constructed. Any waveform that is not a pure sine wave consists of two or more sine waves. Adding the correct frequencies at the proper phase and amplitude will form square waves, sawtooth waves, and other non-sinusoidal waveforms.

A waveform other than a sine wave is called a COMPLEX WAVE. You will see that a complex wave consists of a fundamental frequency plus one or more HARMONIC frequencies. The shape of a non-sinusoidal waveform is dependent upon the type of harmonics present as part of the waveform, their relative amplitudes, and their relative phase relationships. In general, the steeper the sides of a waveform, that is, the more rapid its rise and fall, the more harmonics it contains.

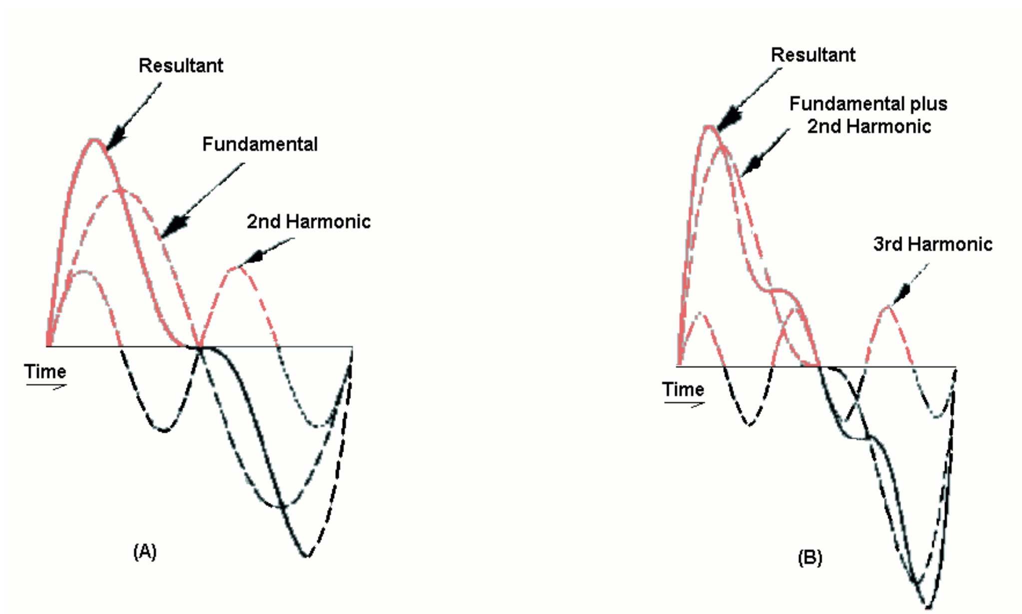
The sine wave which has the lowest frequency in the complex periodic wave is referred to as the FUNDAMENTAL FREQUENCY. The type and number of harmonics included in the waveform are dependent upon the shape of the waveform. Harmonics have two classifications - EVEN numbered and ODD numbered. Harmonics are always a whole number of times higher than the fundamental frequency and are designated by an integer (whole number). For example, the frequency twice as high as the fundamental frequency is the SECOND HARMONIC (or the first even harmonic).



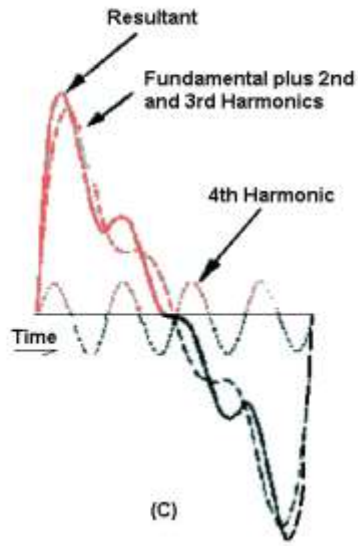
View (A) of the figure on the right compares a square wave with sine waves. Sine wave K is the same frequency as the square wave (its fundamental frequency). If another sine wave (L) of smaller amplitude but three times the frequency (referred to as the third harmonic) is added to sine wave K, curve M is produced. The addition of these two waveforms is accomplished by adding the instantaneous values of both sine waves algebraically. Curve M is called the resultant. Notice that curve M begins to assume the shape of a square wave. Curve M is shown again in view (B).

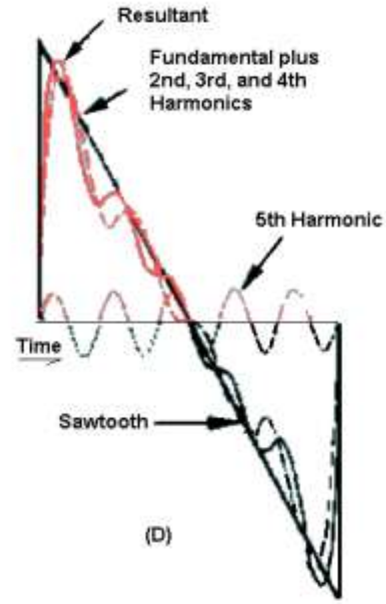
As shown in view (B), when the fifth harmonic (curve N with its decreased amplitude) is added, the sides of the new resultant (curve P) are steeper than before. In view (C), the addition of the seventh harmonic (curve Q), which is of even smaller amplitude, makes the sides of the composite waveform (R) still steeper. The addition of more odd harmonics will bring the composite waveform nearer the shape of the perfect square wave. A perfect square wave is, therefore, composed of an infinite number of odd harmonics. In the composition of square waves, all the odd harmonics cross the reference line in phase with the fundamental.

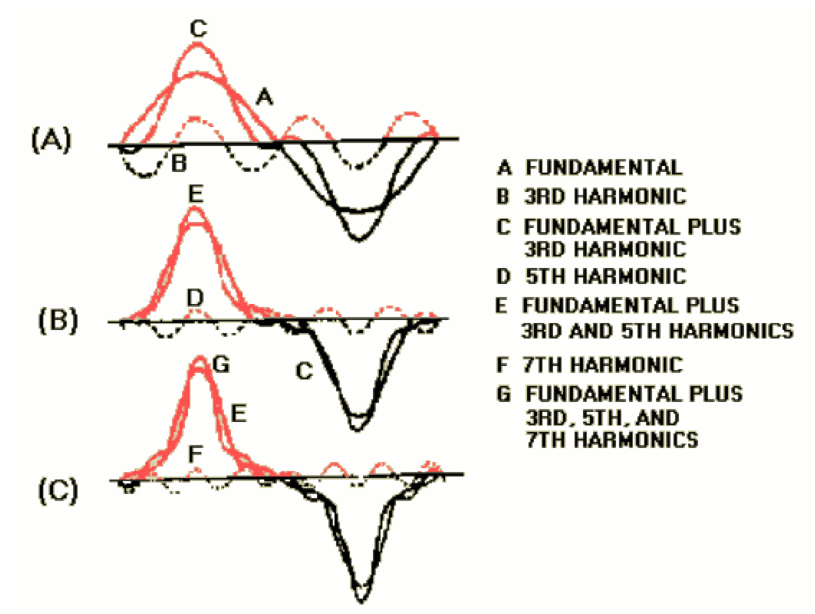
A sawtooth wave, shown on the right, is made up of both even and odd harmonics. Notice that each higher harmonic is added in phase as it crosses the 0 reference in view (A), view (b), view (C on the next page), and view (D on the next page). The resultant, shown in view (D), closely resembles a sawtooth waveform.



The figure below shows the composition of a peaked wave. Notice how the addition of each odd harmonic makes the peak of the resultant higher and the sides steeper. The phase relationship between the harmonics of the peaked wave is different from the phase relationship of the harmonics in the composition of the square wave. In the composition of the square wave, all the odd harmonics cross the reference line in phase with the fundamental. In the peaked wave, harmonics such as the third, seventh, and so forth, cross the reference line 180 degrees out of phase with the fundamental; the fifth, ninth, and so forth, cross the reference line in phase with the fundamental.







The reason these harmonics are of importance, is that their end-product, the characteristically sharp waveforms, have ease of penetration through the skin boundary and can interact with the central nervous system (CNS) directly *(TENS instruments (to alleviate pain) and TASER guns (to inflict pain, or immobilize) function based on this principle, the difference simply being one of magnitude)*. The CNS functions with electric pulses for communication and control. Should the waveforms impressed on the body be of similar waveform as those associated with the CNS or of similar frequencies, or of other frequencies of biological importance (such as brain waves), then these external contributors can cause undesirable biological responses, that may consist of pain, diffuse irritation, etc. Many of the harmonics are within the hearing range (20 to 20,000 Hz), the flicker associated with certain type of lighting is within the range of frequencies that can cause epileptic seizures, so a variety of biological interactions are certain, differentiated in each circumstance due to a large number of variables.

It is in the best interest of anyone subjected to Alternating fields to reduce them to the greatest extent possible following the ALARA principle (As Low As Reasonably Achievable). **Electric Field reduction indoors** can be achieved inexpensively by removing energized devices from the bedside (lamps, alarm clocks, radios, etc.), and using daylight as much as possible during waking hours. **Electric Field reduction outdoors** is greatly aided by tree plantings, as they are in intimate contact with moist soil (grounded), are conductive, and shunt the electric field from a source, preventing it from getting to the other side. This is especially effective when the trees are planted between a house and a nearby power line. **Magnetic Field reduction from ground current** is difficult to accomplish at the individual level owing to the many sources interconnected to the soil, and Neutral Isolation from the supply transformer will greatly help to reroute long-distance cartage of ground current to/from sources. **Magnetic Field reduction from wiring errors,** which are common indoors but were not investigated, is easily accomplished using the protocol included at the end of this Appendix. **Wide-band Energy reduction** is at the core of the biological exposure due to many frequencies involved that are also themselves changing amplitude dynamically depending on what device(s) is(are) energized. Neutral Isolation will help in part from a communal level, regardless of the source, and individual measures as described below will help at the individual level.

Some of those measures, beginning with those that are least-cost include:

a) turning off,

b) unplugging (relative to devices that have stand-by circuit power usage),

c) replacing with alternatives, or

d) limiting usage of:

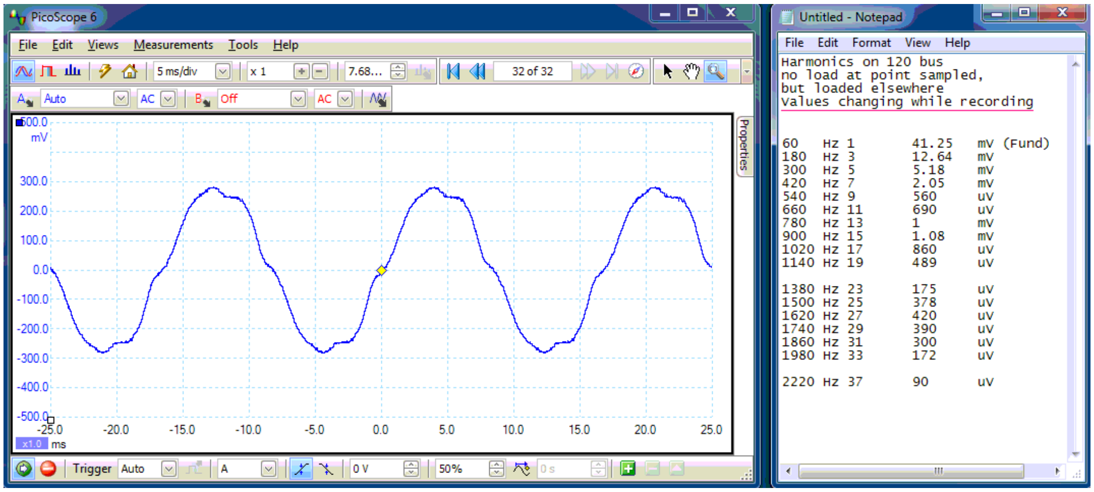
1) Compact Fluorescent lamps,

2) Fluorescent lamps in general,

3) Dimmer switches,

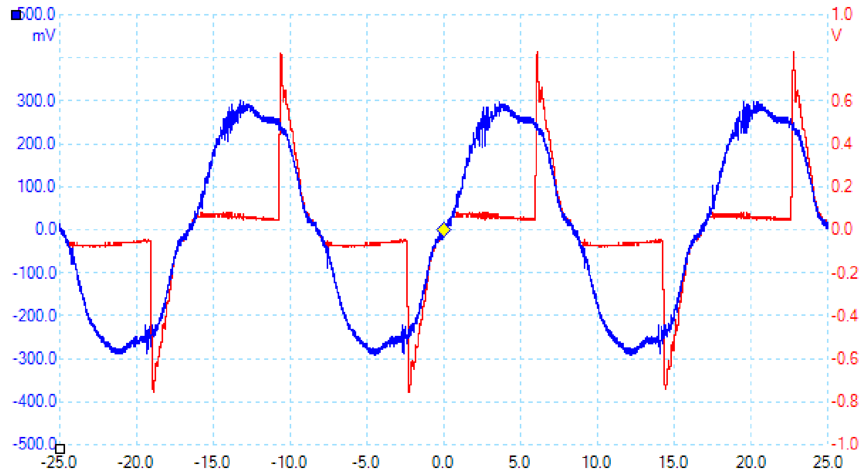
4) Digital devices in general.

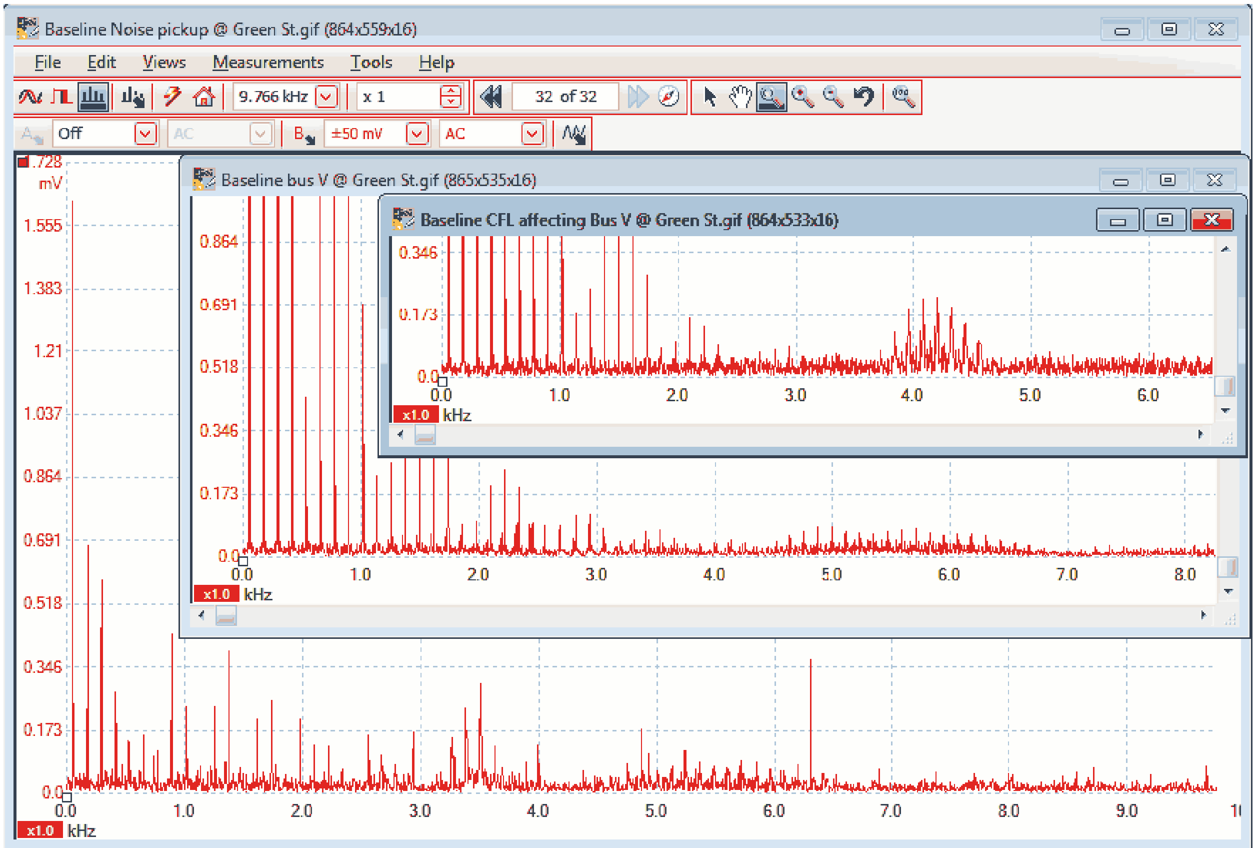
Points of Reference



Above is a graph of one of the 120 V supplies in a house distant from the test sites. Note that although the 120 V is reasonably smooth, whatever loads are in service before the point of measurement, they impact the smoothness of the supplied wave, because there is about 100' of cable between the supply transformer and the applied load, causing a voltage loss between the source and the load. The voltage was sampled with a reduction scheme to protect the equipment, and the peak should be 170 V. So multiplying by 560 will provide calibrated data. Note in the table attached to the graph that all of the detected frequencies were harmonics, and they quickly diminished in size. Compare that to the table to the right of the Current of a Compact Fluorescent Lamp, and note that some frequencies are not 60 Hz harmonics, and their size does not diminish easily with increase in frequency. Due to Ohm's Law, a voltage will be developed at the panel that will subtract from the available 120 V that matches the waveform of the CFL current, highlighted to the right in red. A voltage will also be produced at the neutral/ground wire that will also match the waveform. However, since the load (house) and the source (transformer) are both grounded, some of the current will flow through the soil matching the frequency characteristics of the CFL signature.

Harmonics on 120 bus Current –				F	Harm #	Value	
Compact Fluorescent				1260 Hz	21	13.6	mV
F	Harm #	Value		1343 Hz		5.6	mV
60 Hz	1	132	mV (Fund)	1380 Hz	23	13	mV
180 Hz	3	107	mV	1464 Hz		5.7	mV
300 Hz	5	72	mV	1500 Hz	25	11	mV
420 Hz	7	50	mV	1585 Hz		5.7	mV
505 Hz		3	mV	1620 Hz	27	10.4	mV
540 Hz	9	36	mV	1704 Hz		5.8	mV
624 Hz		2.9	mV	1740 Hz	29	11.4	mV
660 Hz	11	27	mV	1823 Hz		5.5	mV
744 Hz		4	mV	1860 Hz	31	10.1	mV
780 Hz	13	18	mV	1943 Hz		7.5	mV
860 Hz		4.3	mV	1980 Hz	33	9.6	mV
900 Hz	15	19	mV	2063 Hz		7.6	mV
984 Hz		4.7	mV	2100 Hz	35	8.3	mV
1020 Hz	17	19	mV	2183 Hz		8.4	mV
1103 Hz		4.8	mV	2220 Hz	37	7.8	mV
1140 Hz	19	16.5	mV	2303 Hz		7.9	mV
1224 Hz		5.5	mV	2340 Hz	39	8.2	mV
				2424 Hz		9	mV





Pictured above is measurement of Voltage using the same scale to qualify the Picoscope and the impact of a single low wattage device, namely a Compact Fluorescent Lamp (CFL), rated at 14 Watts.

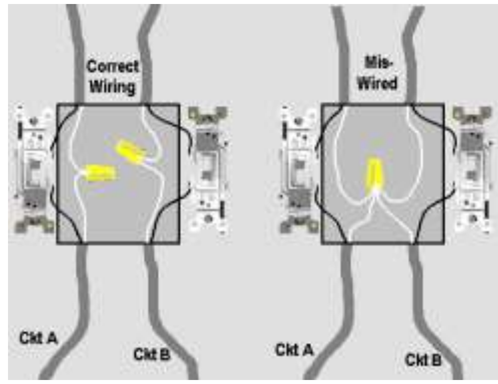
The appliance wattage rating implies a current flow of 116 milliAmps (mA) or 0.116 Amps. What should be enlightening is that for a system where the typical minimum full-load circuit specification is 15 Amps (common across North America), such a low current "energy saving" appliance should not impact the Voltage provided to it. But it does.

Careful observation of the Red waveform in the last picture on the previous page, and its scale, will disclose that the little CFL is using instantaneous current demands, twice per cycle, of 800 mA, or about 7 times the RMS wattage (*RMS being a historical construct whereby all AC power usage can be directly compared to DC power usage. For instance when 120 V is quoted, the voltage is given in RMS values, although the peak is actually 170 volts, twice per cycle*.).

What can be noted from the picture above is that the Picoscope is a very sensitive device, and with leads connected but without any signal input, it will pick up stray signals from any Electric field source nearby (the lower graph). The moment voltage is provided to the cord being measured, a voltage is sensed by the Picoscope, and a corresponding spectrum emerges, specific to 60 Hz and the various power frequency harmonics present from whatever loads are applied to the bus measured, elsewhere in the house (the middle graph, 45 mV @ 60 Hz vs. a prior 1.5 mV). When the CFL is energized (top), the power frequency harmonics below 2 KHZ remain unaffected, but those above 2 KHz emerge as a new signature specific to the CFL, along with a diffuse but pervasive increase in the electrical noise floor.

When one considers that the typical North American home is outfitted with NM/Romex wire, and that structural materials are transparent to Alternating Electric fields, it should be obvious that the electrical noise emissions from even a single CFL become a whole-body exposure phenomenon.

Protocol for Wiring Error Tracing and Correction

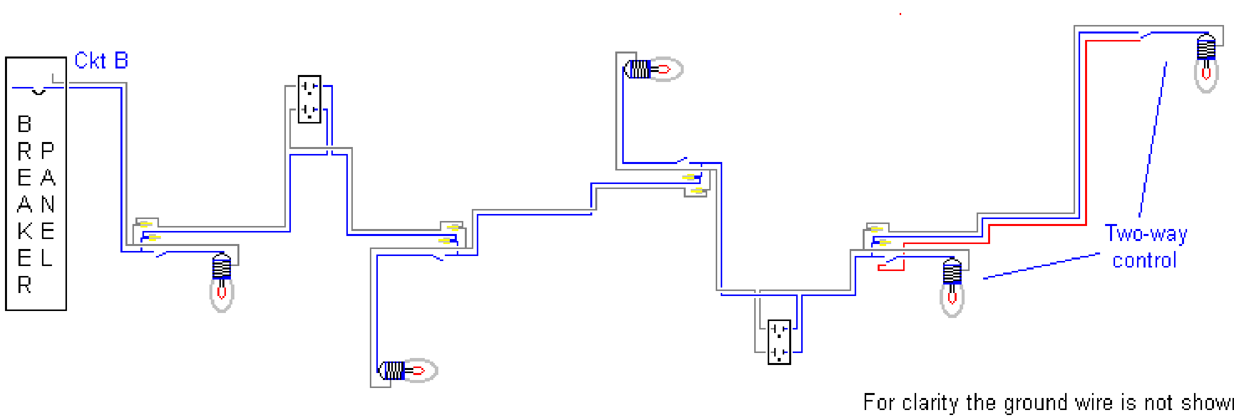


As long as the Supply and Return wiring are in the same cable as shown in the simplified sketch below, their respective currents' Magnetic fields are of opposite polarity and cancel except within a foot or so of the cable. If the return wiring for one circuit is interconnected with another at a junction box with a couple of switches, as an example and as shown on the sketch to the right, then the return current sees more than one path back to the panel, the supply and return currents no longer cancel, and produce a magnetic field in free space bounded by the routes of both circuits. The magnetic field will exist whenever either circuit is in use.

Wiring errors can happen inadvertently, such as a neutral insulation being scratched in the process of inserting a switch or outlet into its box. This may create an instantaneous Neutral to Ground fault. Another is where Neutrals from two or more separate circuits are interconnected at a common meeting place, like switches in a common box, as shown in the above sketch.

To test for wiring errors, open all breakers. Lift a single Neutral from the neutral bar and check for voltage, if there is no voltage (*voltage indicates a more complex wiring error*) then check for continuity between the lifted neutral and the neutral bar. The two possible outcomes are continuity or no continuity. Continuity indicates a wiring error, because with all circuit breakers turned off, and the neutral lifted from the panel, it should have not return connection back to the panel anywhere, as per the sketch depicting a typical circuit below. No continuity indicates a properly wired circuit.

What remains for the electrician is to identify the breaker(s) associated with the respective circuit, turn it (them) off, turn off all other circuit breakers mis-wired to prevent a current back-feed, and lift the Neutral from the Neutral bar. A signal can then be injected (or a continuity test set up) between the neutral and the neutral bar, and the signal will follow the path of, and be traceable through, the entire length of the route of the interconnected circuits. The time-consuming aspect is that several points of use may need to be opened, sequentially, to identify where the wiring error exists. When the wiring error is found and corrected, the signal will no longer have a circuit loop to follow, and it will stop. Signal injection elsewhere will produce unpredictable results. When more than one circuit is mis-wired, it is likely that two or more are interconnected. What will then occur is that when one circuit error is traced, two or more will be corrected. So re-testing is required.



Appendix C: Multiple points of cancellation

For the North American market, residential power is delivered via two buses that are out of phase, or opposite polarity. Under ideal conditions, two matching loads powered from the different buses will cancel at their junction point, being the neutral. Under normal and non-ideal conditions some cancellation will not occur and a return current will attempt to flow back to the source transformer via the neutral. The only way to measure the Instantaneous contribution to the Neutral current from a residence is to measure both energized bus leads simultaneously. From an exposure perspective, without neutral redundancy, the matching currents on the wires to a residence are of opposite polarity and cause almost complete field cancellation except within a few inches to one foot from the cable.

All residential power in North America is provided as three phases, each separate from the other by 120 degrees. This can be visualized by considering a generator whose output consists of three windings physically 120 degrees apart. As the exciting coil spins within them, the voltages and currents in each of the output coils will be 120 electrical degrees separate from the others. At 60 Hz, 120 degrees would be 5.5 milliseconds of time difference. As a three phase system, if three identical loads were applied to each phase, they would cancel at their junction point, being the neutral. Under normal and non-ideal conditions some cancellation will not occur and a voltage will try to develop at the system neutral that directly corresponds to the amount of non-canceled current. Since all distribution substations have an excellent underground grid of bare wire designed to provide a very intimate contact with the earth's moisture layer, which is defined as the zero voltage reference, any attempt to develop voltage directly translates to current that will flow between the neutral at the substation and the neutrals attached to the various circuits, and underground via their multiple ground contacts scattered throughout the geographic service area.

When the power system Primary is a WYE configuration, the voltage is 7200. At a neighborhood transformer this translates to a voltage step-down of 7200/120, or 60 to 1. The opposite is true for current, in that a step-down in voltage is equivalent to a step-up in current. So for each 60 Amps of customer usage, there will only be 1 Amp of current flow in the primary at 7200 V. Since most homes' average power is no more than about 7 Amps, this translates to about 1/10 Amp on the primary. This implies that the <u>Primary fields will be mostly Electric and minimally Magnetic</u>. When the power is conveyed by Transmission lines at 69,000 Volts, a similar phenomenon occurs in that to arrive at 7200 there is a voltage step-down of 9 to 1. That implies that for every 9 amps of current at 7200, there will only be 1 Amp of current at 69,000 V. For 500 KV there is a similar relationship, so that as voltages get progressively higher, the currents get progressively smaller, reinforcing the previous relationship.

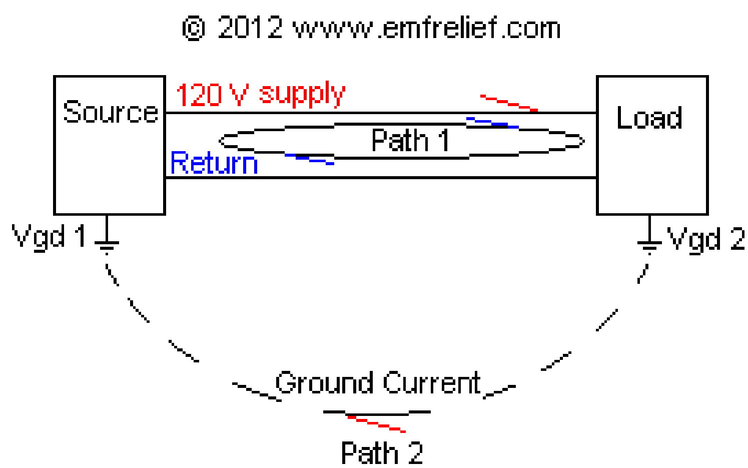
Measuring the difference in the Neutral-Earth voltage at the residence with power on and with power off will give a sense of the different voltage drive affecting current flow into and through the soil. With power off, it will simply be an indicator of Primary grounding current drive, when employed in a WYE configuration, and is also known as **Stray Voltage**. At the transformer this measurement will closely match the one at the residence with power turned off.

The only way to measure the instantaneous contribution to the Neutral current from a supply transformer is to measure both output leads simultaneously, which is generally not possible.

Appendix D: Ground / Grounding Current

Long distance power cartage suffers from Ohm's Law, which dictates that current flow in a wire will develop a voltage difference from one end to the other. This voltage subtracts from the voltage available at the end furthest from the source. Since electricity requires a round-trip loop between the source and the load, via the Supply and Return wiring, this same phenomenon will also produce a voltage on the return wire. If the return wire is grounded at the generator end and is considered to be at zero volts, at the load end it will no longer be at zero volts, when there is current flow. This phenomenon is easily noticeable, in that the voltage available at the local transformer may be 120, yet 100' away or so, with a little current flow the available voltage is no longer 120, but less, say maybe 118. As long as it remains above 114, all equipment functions properly, so there is great effort to ensure wire sizes are big enough to reduce its resistance, and the accompanying voltage loss to less than 5%.

Since the transformer (the source or generator) and the user premises (the load) are both grounded, and since the ground wire connecting them also has current flow, and two grounds are at slightly different voltages, relative to virgin soil, some current will flow through the soil. This is also known as Stray Current. This “leakage” will cause the feed to a house to be unbalanced (supply and return currents are NOT equal) and produce a concentrated Magnetic field about the feed wire, and a diffuse Magnetic field about the soil where the current may be flowing.



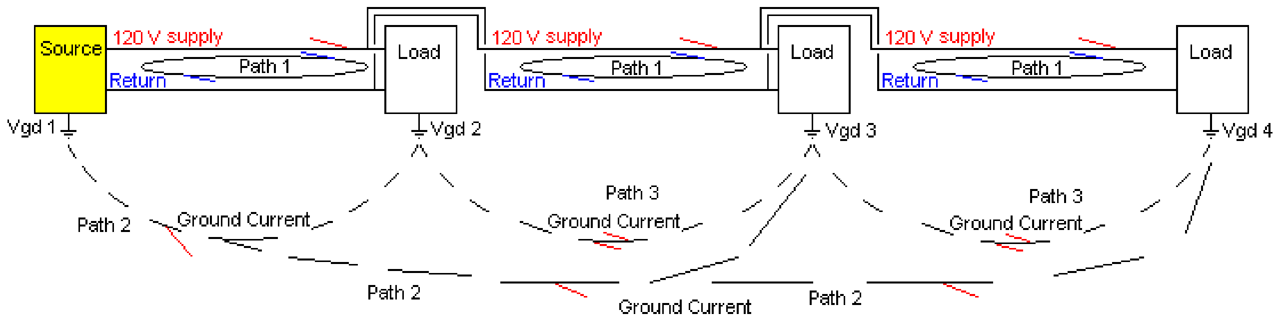
The grounding current does not occur at substations that are for transmission service exclusively, since they are not referenced to earth at both endpoints of their transmission lines (referencing any transmission line at one end is fine, but at both ends it is not). The reason the grounding is not interconnected between geographically distant substations is that there is sufficient DC voltage between such points from the Earth's DC planetary electric system to interfere with the stable operation of the alternating electric system. This causes the ground current phenomenon to be mainly a local phenomenon, wide-area geographically-speaking.

Voltage produces Electric fields, so proximity to power lines or indoor wiring will expose humans. **Current produces Magnetic fields**, so proximity to power lines or indoor wiring problems (a certainty in many homes) will expose humans. Current flowing through the soil, through paths unseen, will cause “unidentifiable” Magnetic fields and expose humans.

The Voltage on the Transmission and Distribution systems, is generally uncompromised, because the power conveyance is mostly in the form of voltage, and minimally current. That is, the Voltage would be a single frequency of 60 Hz. The Distribution Current, in contrast to Transmission current, will have some left-over remnants of customer usage, which would still be minimal due to cancellation effects previously described in Appendix B, and further reduced by the current step-down in the transformer.

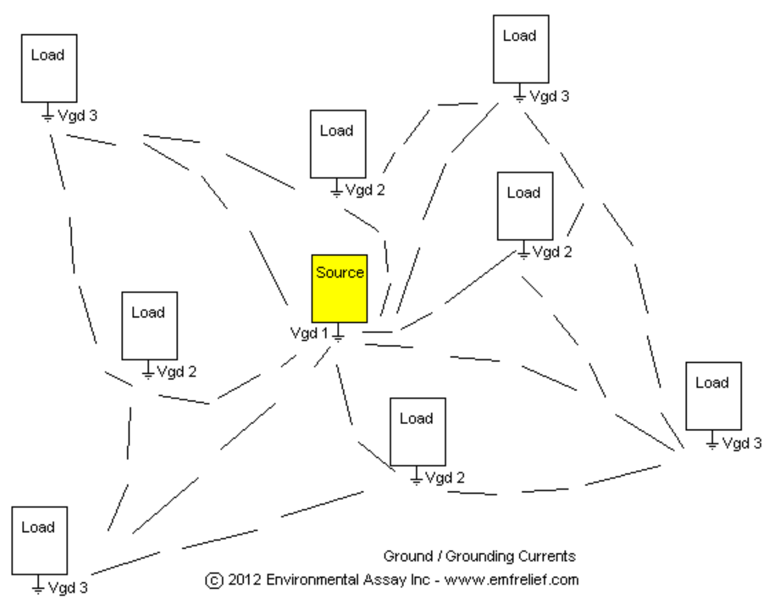
The current in the ground is mostly associated with Distribution systems' current, so it will have lots of non-linearity or Harmonics. Its magnetic field will expose everyone above it. A great portion of those harmonics are within the hearing range and close to other frequencies of possible biological importance, and exposure may cause unintended and widely divergent side effects, based on electric system characteristic and human variables.

When the power source and user is as shown in the simple sketch on the previous page, the possible paths of current are few. When the users are many, due to the many grounding points and the instantaneously varying potentials, the picture gets more complex, as shown below. Since the supply and return wiring are next to each other, there is interaction between their currents' magnetic fields, and a resultant restrictive effect. However, since the current flowing through the soil may not be immediately next to supply or return wiring, there is little interaction between its own and any other magnetic fields, and the restrictive effect is not there. The importance of the restrictive effect is that it is more pronounced at higher frequencies, so that there may be a tendency for the higher frequencies to flow through the soil, and the lower frequencies to flow through the wiring.



Ground / Grounding Current – Profile view

When the electric environment involves widely scattered loads as shown in the greatly simplified sketch to the right, with instantaneously varying ground contact voltages, the ground current may flow to/from any load, between loads, and to/from the source. The only means of reducing this flow is by an ungrounded electric system, or by Neutral isolation at the user location.



Ground / Grounding Current – Aerial view

When the authors attempted Ground Current measurement North of the Ewing reference, in open desert, rods were stuck in the soil in an East-West direction, and nothing was detected. One rod was relocated so that the detection arrangement was North-South, and a tell-tale 60 Hz and harmonic signature emerged (*When placing metal rods in the soil such that they "straddle" any possible flow of current, their electric potential will be the same and no voltage will be detected. When placing metal rods in the soil such that they are parallel with the flow of current, may divulge a 60 Hz and harmonic signature, because of the soil's electrical resistance between the rods. This is complicated by the ground current flowing through layers of soil whose depth below the surface is uncertain, and whose eventual route is also uncertain due to the non-homogeneity of the soil*.). Using the HF3851A Gaussmeter the author verified the presence and direction of the ground current, as it lined up with the flow corresponding to a North-South direction, and whose strength was about 1 nT, or about 0.01 mG. The reading should have been zero.

North is at top