History and Interpretation Of Electrical Grounding In Wisconsin

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By

Mark A. Cook
Rural Electric Power Services Manager
Master Electrician
Commercial Electrical Inspector
Designer of Engineering Systems

And

Richard S. Reines
Senior Public Service Engineer

Abstract: This paper discusses the mandatory requirement that electrical distribution systems in Wisconsin be grounded by code. The long history and consequences of this fact are outlined. Many terms are defined and concepts such as 'objectionable current' and 'stray voltage' are discussed.

The idea that commercial and residential power supply systems need to be 'grounded' has been a nearly universal industry standard for a very long time. For all electrical systems, the basis of this standard has one fundamental theme:- that of safety - i.e. the protection of both humans and animals as well as the prevention of fire by electrical causes. Electrical engineers and electricians usually understand this concept well, but the general public may be confused as to why this is necessary and how it came about. The prime reason for grounding is safety and that has recently been exemplified for the citizens of this state all too tragically. A few years ago, the electrocution death of a Wisconsin dairy farmer served as a regrettable reminder of the consequences of poor or non-existent grounding on secondary electrical systems. After an intensive investigation, a condition of non-conformance with basic code provisions, especially those dealing with bonding and grounding, was evident. A letter from the Public Service Commission of Wisconsin (PSCW or Commission) advising personnel from Wisconsin utilities to be extremely wary of the specific situation uncovered stated, "Unsafe electrical systems pose a substantial threat to the farmer, his family, all persons visiting the farm, and the livestock. These unsafe conditions are not tolerable in an informed and technologically competent society as we have in this state."[1] It is an unfortunate reality that an intentionally ungrounded electrical system can deliver energy to a load seemingly allowing it to operate as intended. However, such a system would be exceptionally dangerous for people to use. It would at all times present a severe and uncontrollable hazard to life and limb.

To examine the overall concept of grounding, a popular book on the subject provides a good non-electrical analogy for the importance of a well-grounded system. "The first and most vital element of a sound, safe structure is a <u>solid footing</u> or foundation on which to build the building. If the building or structure does not sit on a solid foundation, there may be continuous structural problems that will lead to unsafe conditions. Likewise, the grounding system serves as the foundation for an electrical service or distribution system supplying electrical energy to the structure. When solidly grounded, the electrical system must be connected to a dependable grounding system. The grounding electrode(s) supports the entire grounding system and makes the earth connection. It must be effective and all grounding paths must be connected to it. This serves as the foundation of the electrical system."[2] This analogy is unambiguous in its description of just how vital and basic proper grounding is to all power delivery systems. After all, who would build a structure on a poor foundation, ignoring its possible collapse soon after the completion of construction?

Some terms need formal definition to comprehend this concept further. One popular source defines the term 'ground' as "(1) A connection to earth for conducting electrical current to and from the earth; (2) The voltage reference point in a circuit (there may or may

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[1] PSCW Electric Div. *Farm Wiring Safety Bulletin* broadcast letter, M. A. Cook, July 6, 1999.
[2] "IAEI Soares Book on Grounding" 8th Ed., International Association of Electrical Inspectors, Richardson, TX, ©2001.

not be an actual (physical) connection to earth); but it is understood that a point in the circuit said to be at ground (nominally zero) potential could be connected to earth without disturbing the operation of the circuit in any way; and (3) A point in the electrical system that has (nominally) zero voltage; ground also designates earth, literally, which is used as a return path for radio waves from an antenna, etc."[3] We know that 'ground current' is current that is defined to exist wholly within the grounding and grounded system structures of an electrical power circuit. Once a current leaves those grounding and grounded structures to enter the structure of the earth, it becomes an 'earth current.' That same source defines earth current as "(1) Current in the ground as a result of natural causes and affecting the magnetic field of the earth, sometimes causing magnetic storms; and (2) Return, fault, leakage, or stray current passing from electrical equipment through the earth."[4] To understand how important the foundation of an effective grounding system is, the scope, rationale, history and legal ramifications of the development of grounding for electrical power supply systems in Wisconsin is discussed in this paper.

One of the above-mentioned sources assures us that "Some features of electrical safety are *so fundamental* (emphasis added) they have appeared in some form in every edition of the National Electric Code (NEC).[5] These include requirements for suitable insulation for (energized) conductors; overcurrent protection for circuits; and grounding of electrical systems and equipment for safety. The grounding of equipment and enclosures, as well as the grounding of one conductor of an electrical power and light system, has been practiced in some quarters since the use of electricity began."[6] This is obviously a very crucial statement. The NEC code language, which began in August of 1897 as the "Rules and Requirements of the Underwriters' Association of the Middle Department for the Installation of Wiring and Apparatus for Light, Heat and Power," applies to the wiring from the utility meter inwards throughout the users' premises. It now devotes an extensive portion of its contents to the subject of grounding. The scope of that area includes grounding and bonding rules, as well as grounding conductors, locations, types, sizes, electrodes, methods, and conditions.

Likewise, a logical counterpart to the NEC, the National Electric Safety Code (NESC) also devotes an ample portion of its contents to this subject. The NESC language applies to the wiring outwards from the utility point of common coupling back to the power generating station. Electrical distribution systems have a long and interesting history in this country. Thomas Edison developed the first convenient long-lasting electric light bulb as well as the mechanisms for generating and distributing electricity to American homes and

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[3] Rudolf F. Graf, ed., *Dictionary of Electronics*, unabridged, Indianapolis, IN, 1978-79
[4] Ibid.
[5] The NEC is adopted in Wisconsin with additions, modifications and deletions by the Dept. of Commerce as Wis. Admin. Code chapter COMM16 and is also called the Wisconsin State Electrical Code, Vol. 2.
[6] IAEI Soares Book on Grounding, op.cit.

businesses in the late 1870's and early 1880's. The first practical DC generating and distribution systems began with his Pearl Street Station in New York City on September 4, 1882. Significantly, for this state the second DC generating station to be energized in the nation was in Appleton, WI just twenty-six days later on September 30, 1882. Much controversy developed between Mr. Edison and George Westinghouse over the practicality of commercial DC electricity versus AC electricity. The impractical use and insurmountable technical difficulties associated with medium voltage, high current DC distribution systems gave way to the adoption and universal use of AC distribution systems before the turn of the century.[7] Since that time, AC electrical distribution systems including classes of components, construction techniques, and design philosophies have been standardized to a relatively uniform degree by electrical utilities and utility regulating bodies throughout the entire planet.

The overall grounding philosophy in both electrical codebooks mentioned above, as well as those for other countries, is essentially the same. They are:(1) to ensure that through solid grounding techniques the voltages to ground of the phase conductors are limited during normal operations, (2) that line voltages are stabilized, and (3) that overvoltages due to causes such as lightning, switching surges, static, accidental contact with higher voltage systems, line-to-ground faults, resonant conditions, and restriking ground faults are minimized. One can never guarantee that any electrical system will forever remain as intact and pristine as it was upon installation. Physical objects deteriorate with age and adverse weather conditions, accidents happen, and sometimes the electrical system can experience a fault.[8] Effective grounding has been purposely created by code authors, as well as by knowledgeable practitioners (electricians, engineers, etc.), to provide a suitable fault current path so that protective devices may operate as intended. This affords us a reasonable level of safety from the consequences of that fault condition. However, because the earth is physically resistive to some unknown degree in each circumstance, this path through ground (as referenced below) cannot be relied upon as the sole fault current path for safe electrical system operation. Other purposely-installed components that are used in conjunction with a well-grounded electrical system provide the complete measure of safety required. By code, this fault current path must be permanent and electrically continuous, it must be capable of safely carrying the maximum fault current likely to be imposed upon it, and it must be of such low impedance that the operation of an overcurrent protective device (fuse, cutout or breaker, e.g.) will surely occur when needed. The NESC states in Rule 215B5a:"Supply circuits shall not be designated to use the earth normally as the sole conductor for any part of the circuit."

[7] F. McDonald, "Let There Be Light – The Electric Utility Industry in Wisconsin 1881 – 1955," American History Research Center, Madison, WI, ©1957

[8] A fault can be defined as the incidental or accidental contact of a phase wire with another phase wire, the grounded (neutral) wire, the grounding wire or any effectively grounded conductive object including the earth.

Distribution systems are designed to carry the energy supplied at the substation through various configurations of wires and safety equipment deliverable on demand to the end user. Different distribution system configurations exist throughout this country and are characterized by differences in conductor arrangements, voltage levels, phase arrangements, and construction standards. Ideally, as in secondary wiring, the loads should be as close to the source as possible. For rural distribution systems, there unfortunately may be many miles between the source and the end user, which presents the distribution system designer with a myriad of challenges unique to this situation. "The universal type of primary distribution system in North America (and nearly exclusively in Wisconsin we may add) is a three-phase, four-wire, multigrounded system, which consists of three phases and a multi-grounded neutral."[9] These systems at their various voltage levels and configurations should be either solidly grounded or 'effectively grounded' meaning they must meet two specific circuit conditions:[10]

1. "The ratio of the zero-sequence reactance to the positive-sequence reactance (X_0/X_1) is positive and less than three."
2. "The ratio of the zero-sequence resistance to the positive-sequence reactance (R_0/X_1) is positive and less than one."

These conditions assure the designer that fault currents will be limited to levels that can both be predicted and be handled safely by the equipment designed into the system. Failure to meet these criteria means unpredictable and hazardous situations can and will exist on the distribution system in times of abnormal conditions. A noted technical organization has published this comment, "The four-wire, multigrounded neutral distribution system is used "exclusively" in North America because of the safety, economic and operating advantages it offers. The windings of the substation transformers servicing the primary system are wye[11] connected and the neutral point (center of the wye) is solidly grounded (see figure 2 following text). The neutral circuit must be a continuous metallic path along the primary routes of the feeder and to every user location."[12] The emphasis on grounding is for operating the necessary protective equipment effectively and providing a low impedance path for unbalance and fault current flow to ground. Secondary to this objective is the opportunity to reduce levels of neutral-to-earth voltages for mitigation of stray voltage[13] and

[9] "EPRI Distribution Grounding Handbook Vol.1", NEETRAC, Forest Park, GA, 1996

[10] IEEE Green Book, IEEE Recommended Practices for Grounding of Industrial and Commercial Power Systems, NY, NY, 1982.

[11] Wye connected means the three phase windings are shaped like the letter 'Y'. One side of each winding is common at the center junction of the three legs of the 'Y' (see Figure 1 following text.)

[12] EPRI Distribution Grounding Handbook Vol.1, Op.Cit.

[13] Stray voltage is defined as a natural phenomenon that can be found at low levels between two contact points in any animal confinement area where electricity is grounded. Electrical systems - including farm systems and utility distribution systems- must be grounded to the earth, by code, to ensure continuous safety and reliability. Inevitably, some current flows through the earth at each point where the electrical system is grounded and a small voltage develops. This voltage is called neutral-to-earth voltage (NEV). When a portion of this NEV is measured between two objects that may be simultaneously contacted by an animal, it is frequently called stray voltage.

step potentials,[14] especially during fault conditions. After all, "accidental ground faults are inevitable."[15]

In the 1913 edition of the NEC, general mandatory grounding was included for low potential AC circuits. One of the fundamental rules that accompanied this provision was that the grounding was required to be made "at the neutral point or wire whenever and wherever it was accessible." This general concept has been consistently repeated in all available support literature for farm, residence, and commercial sites alike over the generations since that time. One source admonishes us that "the purpose of grounding on the circuits that supply the house and other buildings is to prevent the voltage to ground, of the ungrounded conductor or conductors of the circuit, from rising above the normal operating voltage, usually 115 volts (AC, rms) above ground. Also, grounding serves to limit the voltage on the secondary circuit in case of a fault or accidental contact between the high voltage wires and the building wires."[16] Another commonly published source defines this situation:"In residential and farm wiring, one of the wires is always grounded, that is, connected to a water pipe or driven ground rod. It is 'always a white[17] wire,' wired to every 115-volt device, never fused and never switched or interrupted in any way."[18] Newer publications aimed at educating a decidedly younger audience about this subject speak of the same issues. "For protection of persons and equipment, the neutral conductor of electrical distribution systems is connected directly with the earth, a procedure known as 'grounding.' This applies to all electrical distribution systems in use today. An electrical distribution system that has its conductors properly connected to a grounded system will, when a fault occurs, open an overcurrent device or discharge the fault currents to ground."[19] Note that this reference says 'when,' and not 'if,' a fault occurs. Faults occur more often than anyone who works with electricity would wish. They are, as has been stated, an unpleasant fact of life.

With this background information in hand, many of the other aspects of grounding can be discussed. In Wisconsin, there are two agencies given legal authority to deal with the adoption and interpretation of the aforementioned electrical codes on behalf of all state residents and businesses. These are the Department of Commerce for the NEC as adopted in Wisconsin and the Public Service Commission for the NESC as adopted in Wisconsin. One of the responsibilities of the Commission is to ensure that all electric utilities in Wisconsin operate their electrical systems in a safe and reasonably reliable manner. The Commission adopts many such rules under the authority of Wis. Stat. ch. 196, which gives the PSCW

[14] A step potential is a voltage between the feet of an animal or human as it or (s)he walks on the surface of the earth.
[15] IEEE Green Book, Op. Cit.
[16] "Farm Wiring for Light and Power;" C. H. Sprague and E. A. Brand; 1945 Edition, International Correspondence Schools, Scranton, PA, © 1937.
[17] now allowed to also be grey
[18] "Wiring Simplified"; H. P. Richter, 18th ed., Park Publishing. Co., Minneapolis, MN, ©1946.
[19] "Farm Safety for Kids"; I. J. Kroeker, Gateway Publ. Co., Winnepeg, MB, ©1993.

"jurisdiction to supervise and regulate every public utility in this state…." Specifically, under Wis. Stat. § 196.02(3), the PSCW "may adopt reasonable rules …to regulate the mode and manner of all inspections, tests, audits, investigations and hearings" regarding electrical utilities. Wis. Stat. § 196.74 requires all public utilities to "construct, operate and maintain the wires and any related equipment in a manner which is reasonably adequate and safe…" and which directs the Commission to "issue orders or rules, after hearing, requiring electric construction and operating of such wires and equipment to be safe."

In order to discharge its duty, the PSCW has adopted the NESC with suitable additions, deletions, and modifications as the Wisconsin State Electrical Code Vol. 1.[20] It is also known as Wis. Admin. Code ch. PSC 114. The PSCW was given this responsibility in 1922. This code has been revised many times since that date to reflect the needs of the nation and this state. Chapter 114 of the Wis. Admin. Code has the power of law as granted by the Wisconsin legislature to the PSCW. Therefore, the PSCW is the sole state agency that has the authority to duly administer the NESC in Wisconsin. This is documented by Wis. Admin. Code § PSC 114.03(2)(a) which states "The authority for the enforcement of Volume 1, Wisconsin State Electrical Code (NESC) is vested in the Public Service Commission with respect to the installation and operation of circuits or equipment by public utilities ... in the exercise of their functions as utilities ..." A note further explains that "While the PSCW does not have jurisdiction for enforcement of Vol. 1, Wis. State Elec. Code, over parties other than public utilities…, electric utilities are prohibited under s.101.865, Stats. from extending electrical service to premises which are not in compliance with the Wis. State Elec. Code both Volumes 1 and 2." Furthermore, Wis. Admin. Code § PSC 114.002(1) states that the purpose of this chapter "is the practical safeguarding of persons during the … operation …of electric supply… lines and their associated equipment."

All authoritative bodies, as essential to the protection of human lives and animal lives as well as personal and public property, have recognized the requirement that a distribution system be grounded to earth. The NESC affirms in Rule 092D that the arrangement of grounding conductors is subject to the approval of the administrative authority. This section of the NESC also references the issue of 'objectionable current' on grounding conductors. Objectionable currents are not defined in that publication as earth currents, ground currents, or stray voltage (all defined above). NESC Rule 092D says nothing about stray voltage, earth currents, or stray currents for the very reason that they are <u>not</u> objectionable to the designer of the utility distribution systems or to the administrative authority. These are the only two entities that can make the judgment of what constitutes an "objectionable current." Nothing in the language of NESC Rule 092D supports the override

[20] Remember, the NEC is adopted in this state as the Wisconsin State Electrical Code, Vol. 2 by the Department of Commerce.

of either the necessity of grounding or of the number of grounds per mile required by PSC ch. 114.096(1)C mandating at least nine grounds per mile on the neutral conductor throughout this state. The laws of physics assures us that the earth is an integral current pathway for all grounded electrical systems, but as mentioned above regarding the earth as a current path, NESC Rule 215B5a clearly prohibits the earth from being used as the 'sole' conductive path. It is unambiguous that these codes recognize and allow the earth to be "part of" the total current path, but does not allow it for reasons of safety to act as the exclusive path. For this reason, normal currents in the earth from distribution systems can never be considered per se "objectionable." They have to be there because they have to be part of the overall system. Other rules and considerations assure us that the physical wires of the distribution system also cannot serve as the sole return current path. The wires and the earth must therefore share this much-needed function of return current path in a random proportion dictated by the physics of each location. In addition, currents will normally exist on grounding and grounded structures at detectable levels because of induction and coupling effects that are a part of the basic physical nature of electricity and are not there by the ineptitude or wanton neglect of any system designer.

In any closed loop electrical system, the laws of physics dictate absolutely that current will flow when a source voltage is present. If this were not true, we could not predict and design the complex electrical systems that do our bidding so well in this heavily industrialized society. Current flowing in both expected and, in some cases, unexpected pathways is a natural, inevitable, and unavoidable condition of a multigrounded electric distribution system. In addition to other circuit laws, the foundation for our understanding of the physical nature of all electromagnetic phenomena is firmly based on four equations developed by the Scottish mathematician James Clerk Maxwell in 1873.[21] "He is generally regarded as the greatest theoretical physicist of the 19th century. The laws may be summarized as follows[22] with suitable interpretations:

1.) Electric Force: $\nabla \cdot D = \rho$
   An electric charge (voltage) is a source of an electric field. This equation says that electric lines of force begin and end on electric charges (though this is not necessarily true in a changing magnetic field). Also known as Gauss' Law for electricity.
2.) Magnetic Force: $\nabla \cdot B = 0$
   There are no such things as "magnetic charges or monopole magnetic particles," therefore, magnetic lines of force always form

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[21] From the website: http://www.ieee.org/organizations/history_center/general_info/lines_menu.html#equations
[22] $\nabla\cdot$ is the mathematical operator for divergence, $\nabla\times$ is the mathematical operator for curl, D is electric flux density in C/m^2, ρ is the electric charge density in C/ m^2, B is the magnetic flux density in Wb/m^2, E is the electric field in V/m, and H is the Magnetic field in A/m, $\partial / \partial t$ is the form for a partial differential operation with respect to time.

closed loops (and never diverge to infinity from a point source).
Also known as Gauss' Law for magnetism.

3.) Electromagnetic Induction: $\nabla \times E = -\partial B / \partial t$
Voltage is generated in a conductor as it passes through a magnetic field (or cuts magnetic lines of force). This is also known as Faraday's Law – the most basic equation for electric generator or transformer performance.

4.) Magnetic Effect of Electric Current: $\nabla \times H = i + \partial D/\partial t$
A (flowing) electric current is always surrounded by a magnetic field (or lines of force). This is the signature of an active electric current – it generates a characteristic magnetic field. This was the conclusion that Faraday had derived from Oersted's experiment, also called the Ampere-Maxwell Law.

One measure of Maxwell's achievement is the extent to which his equations are still a basic part of the equipment of the electrician and the electrical engineer. The design of tools and practical devices for an enormous range of electrical technologies -- radio, microwave, radar, optical communications, lasers, *power generation and transmission*, electronic components, and others -- must be based on the proper understanding and application of Maxwell's equations."

These laws are so fundamental and so well documented that individuals who suggest interpretations that wholly contradict these laws, especially those involving grounded and grounding circuits, are certainly suspect in their ability to understand and appreciate them. Because of these laws, competent engineers and electricians can solve both simple and complex electrical equations and predict many of the aspects of AC circuit behavior. We know the physical nature and extent of electrical current and voltage interactions, whether they are contained in conductors, wires and other components or in the earth itself. We can make educated assumptions about electrical structures and model complex physical AC systems as circuits and networks composed of lumped or distributed components such as conductors, voltage and current sources, resistances, and impedances that include capacitances and inductances. Electrical phenomena are therefore not mysterious to a trained mind. From these considerations, it can be accurately said that all ground currents and earth currents must abide by well-established circuit laws. Currents in the earth are part of an electromagnetic phenomenon that obey natural laws and whose nature is well described by Maxwell's equations as well as Ohm's Law and Kirchhoff's Laws. They confirm the idea that conducted, coupled, and induced AC currents can and will occur in all physical conductors (the earth being one of those conductors) under the right set of circumstances. While these parameters of current and voltage can be measured in many different ways, it is essential to make the correct and appropriate set of measurements to be in a situation to properly interpret the consequences of the entire circuit.

We have established that where and how currents flow on grounding structures and in the earth are subject to the laws of physics. A simple equation[23] is well-known for the depth of the bulk of the return current in the earth on a distribution system that depends only on the frequency of the AC current and the local soil resistivity. This shows that it is not just an earth surface phenomenon. Return current sees a fully three-dimensional volume of earth for its return path. For the various soils of Wisconsin, the lowest soil resistivity nominally encountered will be in moist clay and will have a value of roughly five ohm-meters. The highest resistivity normally encountered will be for dry sand and gravel soil and will have a value of roughly five thousand ohm-meters. Using this equation for typical power line frequencies and assuming a uniform earth resistivity, the depths will therefore range from as much as 19,700 feet (for 60-Hz currents and sand/gravel soil) to as little as 88 feet (for the rarely seen 50th harmonic – 3000-Hz currents and wet clay soil). This is still well below the earth's surface. The distribution over the entire vertical profile of the earth under the distribution return path, without unusual interfering conditions, will be a statistically "normal" distribution or bell-shaped curve. The bulk of the current will be physically close to the midpoint of the distribution pathway and will tail off considerably as one considers areas above and below this route. That is why so little current is discernable or measurable away from grounding electrode sites on the surface of the earth. The same is true for the horizontal profile. The return currents tend to follow directly beneath the distribution system pathways as the earth return currents are magnetically coupled with the multigrounded neutral conductor and phase conductor currents and cannot cut "cross-country" away from this pathway easily. Surface earth currents are in the microAmp per square meter range while many Amperes of overall return current may be flowing back to the substation or to a balancing node point.

The wavelength of the 60-Hertz voltage and current power signal is extremely long[24] meaning that there will be essentially no difference in phase between any single voltage measurement point and its corresponding remote reference rod point. This is not true for much higher frequency signals. One should avoid phase differences of greater than 1 electrical degree (about 2% error in accuracy) for this measurement. This is 1/360th of a wavelength. For 60 Hz waves, that distance is 8.6 miles. For a distance between a voltage measurement point and a remote reference rod two hundred feet away, the maximum frequency should therefore be limited to13.7 kHz. Measurements containing higher frequencies than this should not use the remote reference method or be proportionately nearer. A recent study of 60 Hz and low harmonic earth currents by the University of Wisconsin determined that the overall magnitude of these currents is extremely low. They

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[23] The equation is $D=2160 * (\rho/f)^{1/2}$ where ρ is the soil resistivity in ohm-meters and f is the power frequency in Hertz. D is in feet. From A. P. Sakis Meliopoulos, *Power System Grounding and Transients – An Introduction*, p 48, Marcel Dekker, nd.

[24] The equation is $\lambda = c/f$ where λ is the wavelength in feet, f is the frequency in Hertz and c is the speed of light equaling 9.8×10^8 feet/sec. For 60 Hz, λ = 16.4 million feet or 3,106 miles.

found that "Electric fields at the farms range from roughly one to ten mV/m rms at 60Hz, and the current density ranges from about five to fifty μA/m^2. The effect of isolating the neutral (on these voltages and currents) was not consistent. Neutral isolation might increase, decrease, or have no effect on E-field strengths. Because of the nearness of the power supply, average values at the farm are roughly ten to one thousand times stronger than at the corresponding remote sites. Comparison of signal strength from the two remote sites shows that variations in the natural field and contributions from distant manmade structures can be significant. Even though cultural signals were larger than the naturally occurring currents, levels are significantly lower than what is considered sufficient earth current strength to develop step potentials anywhere near the Public Service Commission's 'level of concern' (see below)."[25]

On the distribution grid, utility grounding wires are doing just what they are designed to do - that is to 'ground' the primary system to earth. One interpretation gives an example of an 'objectionable current' as that which could provide enough energy to actually remove the moisture from the area surrounding the grounding electrode thus making it ineffective. Obviously, ineffective grounds are detrimental to a properly operating and safe electrical system, so this situation should be avoided. It is also obvious that many amperes of current need to flow into the ground continuously to provide enough energy to actually dry out the surrounding soil. Another NEC secondary system interpretation, ANSI/IEEE std 446-1987, states that neutral currents that flow through paths other than the intended grounded (neutral) circuit conductors during normal operation of a system will be deemed objectionable if they contribute to any of the following:

(1) Interference with the proper operation of equipment, devices, or systems that are sensitive to electromagnetic interference, such as electronic equipment, communications systems, computer systems, etc.
(2) Interference with the proper sensing and operation of ground-fault protection equipment.
(3) Arcing of sufficient energy to ignite flammable materials.
(4) Detonation of explosives during production, storage, or testing.
(5) Overheating due to heat generated in raceways, etc., as a result of stray current.

The issue of the relevance of ground currents to farms is close to being resolved in a recent Michigan case. This decision was issued and served on April 22, 2003, by the Administrative Law Judge (ALJ) assigned to the case. It must still be accepted or rejected by the Michigan Public Service Commission (MPSC). On April 22, 1998, the Attorney

[25] Alumbaugh, D.L. and Pellerin, L.; *Results of the University of Wisconsin Stray Voltage-Earth Current Measurement Experiment*, Univ. of Wis., Madison, WI, 2002

General (AG) of the state of Michigan filed a stray voltage complaint against Consumers Energy Company (Consumers), which the MPSC docketed as Case No. U-11684. The record in this case consists of 41 volumes of transcripts totaling 4,648 pages and 315 exhibits being admitted. A particularly controversial issue raised by the AG's complaint concerns the AG's assertion that Consumers has intentionally used the earth and private property for more than 30 years as a conductor for return current in violation of the NESC and MPSC Rules and that this condition exacerbated a stray voltage problem. The conclusion of this case states:the ALJ finds that the AG's complaint should be dismissed. The ALJ finds that the AG has the burden of proof to show by the preponderance of the evidence the allegations set forth in its complaint. The ALJ finds that the AG has failed to show a stray voltage problem in Consumers' service territory or, that Consumers has violated the NESC or MPSC rules, or negligently operated or maintained its distribution system. Therefore, the ALJ recommends that the Commission dismiss with prejudice the AG's complaint in its entirety. PSCW staff agrees with this position. This is an important decision in that it affirms the right of utilities to use the multigrounded distribution system including the earth itself according to the provisions of all applicable codes.[26]

In Wisconsin, PSCW orders 05-EI-106 and 05-EI-115, as well as NESC Rule 097D2 as modified in Wis. Admin. Code ch. PSC 114, describe reasonably safe methods to reduce current on grounding conductors if they contribute to stray voltage conditions, i.e. a current flowing through a farm animal that exceeds the PSCW "level of concern."[27] The measurement protocol for acquiring stray voltage numbers is prescribed by those orders.[28] One important point of view is to consider that normal ground and earth currents found on system grounding conductors (whether produced by conduction or by induction) that cause low levels of neutral-to-earth voltages are <u>not</u> per se objectionable. On livestock facilities in Wisconsin, PSCW rules dictate that the utility may isolate a farm for a 90-day period if the primary system contributes more than 0.5 Volt of animal contact voltage across a 500-Ohm resistor (equivalent to 1 milliAmp of animal contact current). They must consequently

[26] Found at http://www.cis.state.mi.us/cgi-bin/mpsc/vieworder.cgi?filename=/mpsc/orders/alj/2003/u11684pfd.htm

[27] In Wisconsin, the "level of concern" is derived from the 1996 PSC docket 05-EI-115. In that docket, the "level of concern" is defined as 2 milliamps, AC, rms (root mean square), steady-state or 1 volt, AC, rms, steady-state across a 500-ohm resistor in the cow contact area ("steady-state" is defined by the Institute of Electrical and Electronics Engineers (IEEE) as "the value of a current or voltage after all transients have decayed to a negligible value"). The state of Wisconsin deems that this level of voltage/current is an amount of electricity where some form of mitigative action is taken on the farmer's behalf, although only some small percentage of cows may actually perceive its presence. The "level of concern" is not a damage level. Instead, it is a very conservative, pre-injury level, below the point where moderate avoidance behavior is likely to occur and well below where a cow's behavior or milk production would be harmed. The "level of concern" is further broken down into two parts. The first part is a 1-milliamp contribution from the utility, at which level mitigative action must be taken by that utility to reduce its contribution to below the 1-milliamp level. The second part is a 1-milliamp contribution from the farm system, at which level mitigative action should be taken by the farmer.

[28] The Phase II Protocol is a comprehensive test strategy designed by the PSC and used to determine all sources of cow contact voltage from on-farm and off-farm sources. There are five specific tests, as well as an overall data record form. The five tests are: (1) the load box test, (2) the secondary neutral voltage drop test, (3) the signature test, (4) the primary profile, and (5) the twenty-four hour test. Other tests may be performed as necessary to give a complete account of the electrical activity on the farm.

install such mitigation as needed to reduce their contribution to less than that level. Any livestock facility customer has the option to install an approved isolation device on his/her farm on-demand according to PSCW orders if the utility contribution is less than that level and the customer wishes to limit any possible contribution from utility neutral voltage sources. In that case, on-farm neutral-to-earth voltages from utility contributions can easily be reduced to an undefined but least-impact level. The usual rule-of-thumb is a 10-to-1 reduction of the primary current appearing on the secondary system. This requires that accurate measurements of the proper ground referenced signals and not any "floating" signals be made to ascertain the levels of animal contact voltage and neutral-to-earth voltage involved. Methodologies for proper measurement techniques that exclude spurious high frequency signals or "floating signals" have been discussed in a previous PSCW document.[29] Any customer has the right to isolate his/her secondary electrical system by a variety of other methods allowed by code without utility or PSCW involvement, but must attest that their facility is wired according to the relevant provisions of the NEC.

Most earth currents and ground currents are the result of local 120-volt on-farm loads. From the PSCW utility stray voltage database, it has been determined that stray voltage levels above the 0.5 volt action level arise from solely on-farm sources 1/3 of the time, from solely off-farm sources 1/3 of the time, and from a combination of both sources 1/3 of the time. This implies that on-farm sources contribute to elevated levels of stray voltage about 50% of the time. On a distribution system operating at 14,400 volts primary voltage and 120 volts secondary voltage, the use of a fixed 120-volt electrical load results in 120 times less current on the primary side compared to the secondary side. That is to say that an 80% efficient 1.5 hp motor operating on 120-Volts AC will draw nearly 12.0 Amps from the secondary service while drawing only 0.1 Amps from the primary service. In a non-isolated condition, this return current of 0.1 Amps may use the farm grounding system as part of its return path. On every non-isolated farm, the secondary return current will share the primary and secondary ground return paths. The primary current will do likewise. Thus, they are intermixed to some degree and as such are inseparable. Such load currents can never meet the definition of "objectionable" for either the primary or the secondary system as these load currents are a physical reality strictly due to the use of electricity by the consumer.

Further, interpretation of the NESC assures us that once a distribution system has been established as a multi-grounded system, as it has in Wisconsin since the beginning of electrical usage, it must remain a multi-grounded system. All of the 118 Wisconsin electric utilities use a multi-grounded system, as required by code. Rules 096B and 096C of the NESC, with changes to NESC rule 096C as adopted in Wisconsin, <u>do not</u> authorize utilities

[29] "Measurement protocols – Facts and Misconceptions;" R. Reines, M. Cook & J. Loock, PSC White Paper Series, July 2000

to serve customers with ungrounded systems. These rules refer to single-grounded (whether uni-grounded or delta systems) and multi-grounded systems. Wholly ungrounded systems are not mentioned. Wis. Admin. Code § PSC 114.02(1) states, "The purpose of this chapter is the practical safeguarding of persons during the installation, operation, or maintenance of electric supply and communication lines and associated equipment. This chapter contains minimum provisions considered necessary for the safety of employees and the public. This chapter is not intended as a design specification or an instruction manual." Consent for the design specification of the type of grounding conductor that accompanies any system is always up to the administrative authority having jurisdiction and the state licensed electrical designer of engineering systems responsible for the utility system design and installation.

The NESC is a minimum safety standard subject to administrative interpretation and modification. This administrative interpretation of the NESC states that, regardless of "system" transformation, an equipment grounding/grounded conductor (primary neutral conductor) shall be installed with the primary ungrounded phase (intentionally ungrounded) system conductors for reasons of safety. This conductor may or may not be used as a current carrying grounded neutral, but it shall be available, permanent, and electrically continuous. Wisconsin law requires that this primary neutral be grounded to earth at every transformer and, in total, at no fewer than nine locations per mile (Wis. Admin. Code § PSC 114.096(1)). The PSCW has recently modified the NESC to require that for newly constructed rural distribution systems the primary neutral be grounded at each pole.[30] For safety reasons, Wisconsin has adopted a more strict interpretation of the NESC, imposing more stringent grounding requirements than any other state. The PSCW utility database has shown that this has been beneficial in the reduction of overall levels of both primary neutral-to-earth voltage and stray voltage. PSCW staff provided a history and interpretation paper dealing with the number of grounds per mile for the distribution system in Wisconsin a few years ago.[31]

The idea of a grounded electrical system design is implicit for all transformations as a matter of minimum safety. An interpretation has also been provided on specific rules for ungrounded secondary side transformer installations.[32] Historically speaking, delta systems are an out-of-the-ordinary and obsolete configuration of a three-phase primary system. Wholly ungrounded systems of any transformation cannot and do not exist in reality. As mentioned above, the physics of electricity assure us that any purposely ungrounded distribution phase conductor is 'effectively high impedance grounded' through a distributed capacitance (see figure 3 following text) and mutual inductance to all ground and grounded structures in its vicinity. One cannot situate such an ungrounded conductor in any manner

[30] Wis. Admin. Code § PSC 114.096C
[31] PSCW Electric Div. Broadcast letter "Re: Grounding Guidelines"; M. A. Cook, September 20, 1999.
[32] PSCW Electric Div. Broadcast letter "Re: Ungrounded Transformer Installations"; M. A. Cook, February 22, 1999.

where this is not true. A high impedance AC conductive pathway exists from each phase wire to ground no matter what is intended. The catastrophic consequence of this fact in light of various possible fault scenarios is why electrical distribution systems need to be well grounded.

The design of an electric distribution system should be dictated by its intended use. In order for Wisconsin utilities to construct, operate, and maintain their electric systems in a manner which is reasonably adequate and safe, the electrical systems are required to be solidly grounded. All of the rules in the NEC as adopted in Wisconsin by the Department of Commerce in Wis. Admin. Code ch. COMM16 support this interpretation. Every circuit wired under the NEC in commercial, industrial, or residential applications, without exception, must also be supported with a grounding system or grounded system that is available, permanent, and electrically continuous. The only safe and reliable configuration for a system that is designed to deliver electric energy to consumers in Wisconsin is the multi-grounded distribution system. Grounding is the single most important element of the electrical system in this nation and it must be maintained for the sake of safety for persons and animals in proximity to our electrical system.

In conclusion, the PSCW is the sole state agency that has the authority to duly administer the provisions of the NESC in this state. The requirements of the electric code exist exclusively for safety reasons. They are mandatory and have the force and effect of law. Electrical power systems have been and always will be grounded to earth in Wisconsin. Grounding is the single most important element of the electrical system in this nation and it must be maintained in a way that when the system fails, it fails in such a manner as to be as safe as possible. Most importantly, NESC rules only prohibit the earth from being used as the "sole" conductive current return path. From the laws of physics, the earth will certainly be part of this conductive path, just not the only part. Since the distribution system Wisconsin established to serve this state was created as a multigrounded network, code requires that it remain a multigrounded network in its entirety. Neutral-to-earth voltages, stray voltage, earth and ground current are not per se 'objectionable.' PSCW orders, as well as NESC rules as modified in Wis. Admin. Code ch. PSC 114 describe reasonably safe methods to reduce current on grounding conductors if they contribute to a conducted current flowing through a farm animal that exceeds the PSCW "level of concern."

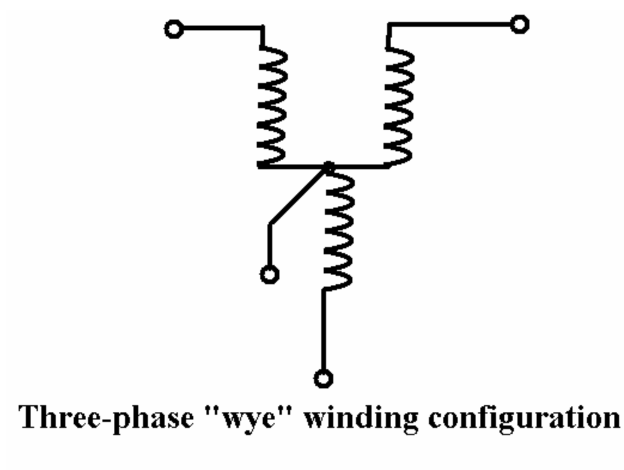

Figure 1: The wye configuration.

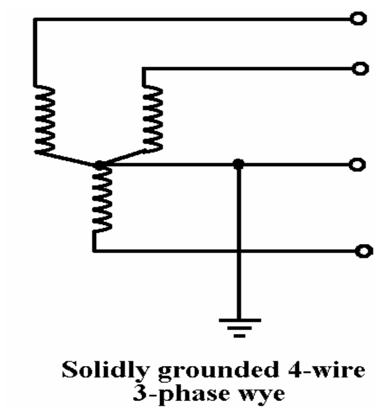

Figure 2: Solidly grounded 3-phase 4-wire wye configuration

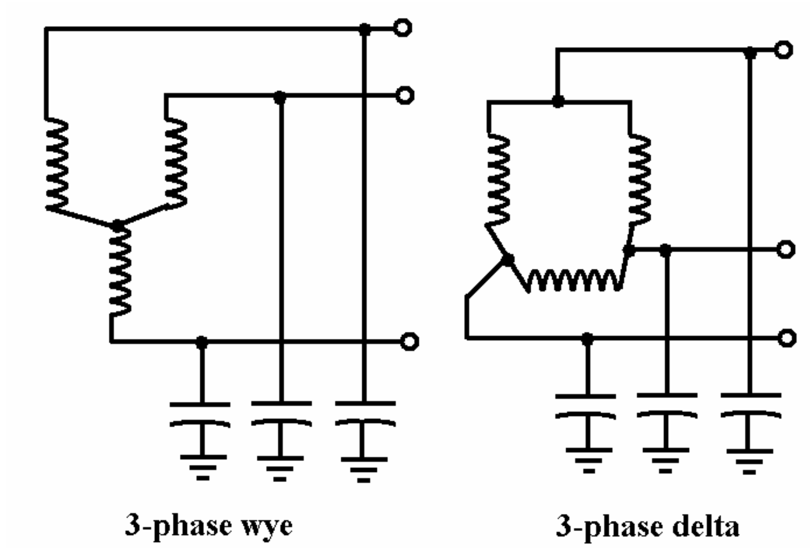

Figure 3: Effective high impedance grounding