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The 3rd Harmonic Blocking Filter: A Well Established Approach to Harmonic Current Mitigation

Despite thousands of successful applications of harmonic blocking technology worldwide, harmonics mitigation remains an elusive subject. This paper will discuss the design and operation of the 3rd harmonic blocking filter, with special attention paid to code and regulation requirements and electrical distribution system benefits.

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It has long been recognized that harmonic currents, particularly the 3rd harmonic, flowing in a wye distribution system serving multiple computer loads, are detrimental to system operation. Problems caused by these harmonic currents include overheated transformers, switchgear and wiring; random circuit breaker tripping; and reduced useable system capacity. Conventional methods used to mitigate the harmful effects of these harmonic currents include k-rated or de-rated transformers, harmonic mitigating transformers (zig-zag and phase shifting,) oversized switchgear, double or triple neutrals, and other "accommodation" techniques. However, it is easier to prevent the flow of harmonic currents than to treat them after they are flowing in the system. The 3rd-harmonic blocking filter is a well-established device that prevents harmonic current flow.

Despite thousands of successful applications of harmonic blocking technology world-wide, harmonics mitigation remains an elusive subject, and questions continue to be raised about how this technology works, is it safe, does it meet code requirements, is it UL listed, what about standards, etc. This paper will discuss the design and operation of the 3rd harmonic blocking filter, with special attention paid to code and regulation requirements and electrical distribution system benefits.

Harmonic currents

Harmonic currents are a direct result of the way in which a switched-mode computer power supply (SMPS) draws current from the system. The input circuit of an SMPS is a bridge rectifier that changes the 120-volt AC input to DC. A capacitor smoothes this DC to eliminate voltage ripples and the resultant DC bus has a voltage of about 170 volts when the AC rms input is 120 volts. Although the AC voltage is a sine wave, the rectifier draws its current in spikes as shown in figure 1. These spikes require that the AC supply system provide harmonic currents, primarily 3rd, 5th and 7th. These harmonic currents do not provide power to the SMPS, but they do take up distribution system capacity. The principal harmonic current is the 3rd (180 Hz) and the amplitude of this current can be equal to or even greater than that of the fundamental current. [Figures 1 and 2]

Harmonic current flow in a wye distribution system

Figure 2 shows the flow of currents in a 3-phase 4-wire distribution system serving motor loads. One of the reasons this type of distribution system is used is that when the loads on all three phases are balanced, and only the 60 Hz fundamental current is considered, the fundamental current cancels in the neutral and the neutral current is zero. If the loads are unbalanced, the neutral current is only the unbalanced current. (Until 1990 the *NEC* permitted downsized neutral wires since the neutral was not considered to be a current-carrying conductor.) However, when SMPS loads are connected as shown in figure 3, each phase wire carries both the 60 Hz fundamental current that supplies power to the computer and the harmonic currents that are there because of the way the SMPS draws its current. While most of the harmonic currents cancel in the neutral wire, just as the 60 Hz currents do, the 3rd harmonic current and other currents divisible by three are additive in the neutral wire. Thus, if the 3rd harmonic current were 100 amps in each phase, the 3rd harmonic current returning to the XO transformer connection along the neutral wire would be 300 amps. While the code still permits downsized neutrals if the system is not powering nonlinear loads, this is the reason for language in *NEC 310.15(B)(4)(b, c) (2002)* that requires neutral conductors to be considered current-carrying conductors when nonlinear (SMPS) loads are present. (Note that there is *no code requirement for double neutrals.)*

System problems caused by 3rd harmonic currents
The effect of current distortion on the actual computer loads within a facility is minimal since the distorted current is caused by operation of these loads. However, the effect of current distortion on distribution systems can be serious, primarily due to the increased current flowing throughout the system. All distribution systems are rms current limited, and the more harmonic current flowing, the less room there is for fundamental current. Since the harmonic current does not deliver any power, its presence uses up system capacity and reduces the number of loads that can be powered. Harmonic currents also increase I2R heat losses throughout the system. The 3rd harmonic current flows in all phase wires and is additive in the neutral wires. It is very possible for this extra current to overload and overheat wires and associated switchboards and panelboards.

Balanced 3rd harmonic currents cannot flow out of a delta primary. Therefore, they circulate in the primary of the transformer where they are dissipated as heat (see figure 3). The current circulating in the transformer delta primary winding does not flow through the primary overcurrent protective device but does contribute to the load on the primary winding. Thus, the transformer primary winding can be overloaded without operating the overcurrent protective device.

Finally, 3rd harmonic currents flowing through the resistance of the electrical system create 3rd harmonic voltage distortion. Phase-to-neutral voltage distortion does not harm the computer power supplies, since it is caused by operation of the supplies. However, high neutral harmonic current flow can lead to neutral-to-ground voltages (noise) that can result in data loss and computer malfunction. The further the computer is from the transformer, the higher these neutral-to-ground voltages will be and the greater the possibility for data loss.

Alternatives for harmonic mitigation
Until introduction of the 3rd harmonic blocking filter (often called a "harmonic suppression system or "HSS"), methods used to mitigate the effects of harmonic currents involved "accommodation" of the currents after they were in the system. A first step was to overbuild the system to handle the extra current. Double-sized neutral wires, oversized switchboards and panelboards and transformers de-rated to less than their full capacity are examples of system overbuilding. To reduce the chance of transformer failure due to overheating, special transformers, known as "k-rated," were designed to be able to handle high harmonic loading, including 3rd harmonic currents circulating in the delta primary, without burning up. On a k-rated transformer, neutral connection lugs are oversized and may be doubled to handle two neutral wires. The transformer core contains more iron to reduce flux density and multiple wires are used in the windings to handle extra currents. The resulting transformer will survive overheating when subjected to high harmonic loading, but the harmonic currents are still present in the system.

Another method of protecting transformers from circulating 3rd harmonic currents without replacing them with k-rated devices is to use a "zig-zag" reactor. The zig-zag reactor contains special windings connected so as to present a low impedance to 3rd harmonic currents. When a zig-zag reactor is connected between the phases and neutral of a wye system, the 3rd harmonic currents are diverted through the device. These currents no longer flow, from the point where the zig-zag is connected in the system, upstream to the transformer. From the point of connection of the zig-zag back to the transformer, the phase wires carry only 60 Hz current and harmonic currents other than 3rd. However, the phase and neutral wires from the zig-zag toward the loads still carry all the harmonic currents, including the 3rd, and double neutral wires are recommended. This device protects the upstream wiring and transformer, but has no effect on the loads or load wiring.

A "zig-zag" transformer can be used to replace the standard transformer in a system. This device has the special windings of the zig-zag reactor built into the transformer secondary so that the 3rd harmonic currents are cancelled in the secondary and do not circulate in the primary winding. Again, the phase and neutral wires from the transformer to the loads still carry all the harmonic currents and double neutral wires are recommended.

The 3rd harmonic blocking filter uses a different approach to mitigate harmonic currents in the distribution system. Its application is based on the same concept that is used in modern medicine, "preventative action." Instead of treating the symptoms of a disease, it is far better to keep the disease from occurring. The HSS is designed to prevent the flow of harmonic currents in the distribution system, rather than treating or accommodating them after they are there.

The HSS consists of a parallel resistive/inductive/capacitive (RLC) network tuned to the 3rd harmonic, or 180 Hz for a 60 Hz fundamental frequency. The electrical characteristics of this type of circuit are such that it has a very high resistance to the flow of 3rd harmonic current and a very low resistance to the flow of the fundamental 60 Hz current. Application of the HSS is shown in figure 4.

The HSS is connected in series between the neutral wire and the transformer XO. All current that flows through the phase wires to the load must return through the neutral. If 3rd harmonic current cannot flow in the neutral, due to the high impedance of the HSS, then no 3rd harmonic current can flow in the phase wires. The damaging 3rd harmonic current is blocked throughout the entire distribution system from the transformer out to the furthest load. There is no 3rd harmonic current circulating in the delta transformer primary because there is no 3rd harmonic current available to circulate. The transformer is now fully protected, by the primary circuit breaker, against overloading. Phase wires have more capacity remaining to carry useful load and double neutrals are not necessary. The neutral, for code purposes, need no longer be considered a current-carrying conductor. Overheating of transformers, switchboards and panelboards, and wiring is eliminated, increasing the lifetime of all system components.

The HSS, the *NEC* and other regulations and concerns

In the reality of the commercial marketplace competitors of a particular technology often raise false concerns in an attempt to detract from the benefits of that technology. As the HSS has been the target of such actions, it is useful to examine the HSS installation in terms of the *Code* and other regulations. A number of issues will be discussed in some detail.

Does the installation of the HSS constitute a "resistance-grounded system?"
Resistance-grounded systems employ an intentional resistance connection between the electrical system neutral and ground."1 Such systems are usually used in medium and high voltage distribution networks to limit ground-fault currents. Impedance grounded systems are permitted in systems of 480–1000 volts, again to limit ground-fault currents. NEC 250.36 (2002). The impedance inserted is usually a high value (100–10,000 ohms depending on the voltage level) designed to limit the fault current due to a phase-to-neutral short to a low figure, e.g., 10 amps. A current sensor on the grounding resistor detects this low current and shunt-trips the protecting breaker. The installation of the HSS, with an AC impedance of 0.05 ohms or less, does not constitute an impedance ground, does not significantly limit the short-circuit current, and is not in violation of this section of the *Code*.[2,3]

What about other grounding language in the Code?
The following code references are to *NEC* 2002*.* Words in bold refer to the labels in figure 4.

Article 100 defines a separately derived system and Section 250.20(D) establishes *Section 250.30* as the controlling language. *Section 250.30(A)* defines exactly the manner in which the HSS is applied to the electrical distribution system. Conductors of interest include:

1. The grounded conductor (**NEUTRAL**), *Section 250.26, Conductor to be grounded*..., as follows: (*2) Single-phase, 3-wire: the neutral conductor.* and *(5) Multi-phase systems in which one phase*

is used as in (2) above: the neutral conductor.

2. The **GROUNDING ELECTRODE**, *Section 250.30(A)(4), Grounding Electrode, (1) an effectively grounded structural metal member of the structure*

3. The grounding electrode conductor (**GEC**), *Section 250.30(B)(2), A grounding electrode conductor shall be used to connect the equipment grounding conductors, the service equipment enclosure, and, where the system is grounded, the grounded service conductor to the grounding electrode…*

4. The equipment grounding conductor (**EGC**), *Section 250.110, …exposed non-current-carrying metal parts…shall be grounded …*

5. The bonding jumper, Section 250.30 (A)(1) refers to *Section 250.28, For a grounded system, an unspliced main bonding jumper shall be used to connect the equipment grounding conductor(s) …to the grounded conductor of the system…*

6. Equipment bonding jumper (**EBJ**), *Section 250.30(A5), Where a bonding jumper is run with the derived phase conductors from the source of a separately derived system…*

In figure 4, it can be seen that the **NEUTRAL** is directly connected inside the filter to the **EGC**s. The connections are with, "…listed pressure connectors…", *NEC 250.70.* The connections are all made within the filter enclosure directly at a, *"…bus bar…," Section 250.30(A)(3)(b)*, which serves as the main bonding jumper. The **GEC** is also connected to the same point and goes from that point directly, *"shall be installed in one continuous length without a splice or joint…" , NEC 250.64(C),* to **a GROUNDING ELECTRODE in accordance with 250.30(A)(4)**. Further, the transformer enclosure is correctly connected to the **NEUTRAL** by the EGC, *NEC 250.118*, as are all enclosures and conduit in the distribution system. The *Code* requires transformer enclosure grounding, for safety, *NEC 450.10*, and as explained above, the HSS and its associated transformer connections follow exactly *NEC* definitions and language. The HSS was designed to meet *NEC* requirements. Consultation with a number of *NEC* board members, who are experts on grounding, has confirmed HSS code compliance. Any suggestion that the HSS installation does not meet *NEC* requirements is simply not valid.

What about "arcing" faults due to phase-to-neutral shorts?
The purpose of grounding requirements in the *NEC* is to ensure that health and safety are not compromised. Adjacent pieces of equipment that can be energized must be tied together to a common ground so that dangerous potentials do not exist between equipment cabinets. Proper grounding must ensure that protective devices will operate correctly under fault conditions. The impedance of the HSS is less than 0.05 ohms, and decreases with increasing HSS kVA rating. Under short-circuit conditions, the current flowing through the HSS is more than sufficient to trip the phase breakers. It should be noted that the inductive elements of the HSS, which carry the current under fault conditions, are UL listed components and have been tested to carry full rated current for the size of the system in which they are used.

What about UL?
In most jurisdictions, it is impossible to sell or install electrical equipment that has not been inspected by a qualified third party testing laboratory. Therefore, before the neutral blocking filter could be offered on the market, it was submitted to UL for testing. All neutral blocking filters are UL listed.[4]

What about voltage distortion?
Voltage distortion caused by harmonic current flow is a natural result of harmonic currents flowing through the impedance of a system. In commercial facilities, where multiple computers are powered, the computers often draw enough 3rd harmonic current through the supply wires to generate as much as 10 percent voltage distortion. (The further the load is from the transformer,

the higher this distortion.) While this might seem to be cause for concern, the truth is that this distortion is caused by operation of the SMPSs and certainly does not interfere with their operation. When the HSS is installed at the transformer, 3rd harmonic currents no longer flow in the phase wires. However, the high 180 Hz impedance of the device, results in phase-to-neutral 3rd harmonic voltage equal to, or sometimes higher than, the natural voltage distortion. Again, this does not interfere with the SMPS operation.

What about high voltage distortion damaging the rectifiers or capacitors in the SMPS?
It has already been mentioned that the SMPS during its operation causes 3rd harmonic voltage distortion. Research studies have been conducted to thoroughly investigate the effect of voltage distortion on the power supplies. Contrary to any suggestion that reduced peak voltage would increase power supply losses, a definitive study has determined that addition of 10 percent 3rd harmonic voltage distortion to the 60 Hz wave actually increased the efficiency of the power supply by as much as 6.1 percent.5 Further, a computer modeling study carried out at a major university, found that installation of the HSS reduced the strain on rectifiers and would be expected to lead to increased lifetime for the SMPS components.6 Neither of these studies is compatible with the suggestion that use of the HSS could lead to equipment failure. There has never been any study that shows that erratic or subtle malfunctions are caused by powering SMPSs with distorted voltage. If anything, erratic operation can be caused by neutral-to-ground voltages.

What about neutral-to-ground voltage?
When 3rd harmonic currents flow in neutral wires, but not in the safety ground wires, the result is a voltage generated between the neutral and ground. When the combined 3rd harmonic currents from the phases flow in the neutral, this voltage can reach more than 10 volts. This voltage can interfere with data transmission in shielded wires and can result in lost data or data corruption. By preventing the flow of 3rd harmonic currents in any neutral wires out to the furthest load, the HSS completely eliminates 3rd harmonic neutral-to-ground voltage, thereby increasing the reliability of data transmission.

What about computer ride through?
Reduction in peak voltage, whether caused by the operation of the SMPS or by installation of an HSS, reduces voltage-out ride through time. Ride through time is why facilities install uninterruptible power supplies (UPSs) on their critical computer loads. Most facilities that install HSS also have large UPSs and generators for support. Some use small UPSs at critical loads. The switching time for small UPSs is between 10 and 50 milliseconds. A published study showed that a computer would function for about 175 milliseconds on complete input voltage loss if the input rms voltage were 120 volts, (the peak voltage would be about 170 volts.)7 HSS flat topping has never reduced the peak voltage below 150 volts, which would result in a ride through time of no less than 136 milliseconds. Since the majority of complete power outages last for longer than 200 milliseconds, the computer supply will not ride through the outage either with or without the HSS. That is the reason for the UPS, and it is clear that, even in the worst case, with an HSS the computer would operate long enough for the UPS to take over. The same study showed that computers would operate indefinitely with an input voltage of only 50 percent of the rated voltage—60 volts. It should be clear that the HSS does not affect computer ride through in the real operating world.

What about IEEE 519?
There is a mistaken belief that IEEE 519 regulates harmonic voltage distortion levels everywhere in a distribution system. In reality, this document was developed to limit current and voltage distortion at the utility connection to multiple customers, called the Point of Common Coupling (PCC)8 It was developed to deal with 3-phase industrial systems and was never intended to apply, and does not apply, to phase-to-neutral voltage distortion at the secondary of a transformer that is internal to a facility. (As has been discussed above, phase-to-neutral voltage distortion has no negative effects on operation of computer power supplies.) Any references to IEEE 519 with regard to voltage distortion and the HSS are an incorrect application of this standard.

Benefits of the HSS

Now that issues with the HSS and any code, regulation, or operation factors have been discussed, it is useful to examine in some detail the benefits of installing this technology to mitigate harmonic currents. Four areas will be discussed: 1) enhanced life safety; 2) increased system capacity; 3) greater reliability; 4) energy and operating cost savings.

Enhanced life safety

Third harmonic currents flowing in the system can overload transformers, switchgear, and wiring. With neutral currents greater than the phase currents, facilities, and particularly older facilities, are at risk from overheated wiring leading to fires. Transformers with high 3rd harmonic currents circulating in the primary, and unprotected against overloading, can fail or catch fire. One study found that 33 percent of telecommunication fires were caused by failures of power systems or components.9 By eliminating 3rd harmonic currents from the transformer to the furthest outlet, the HSS eliminates the risk of over-current caused fires.

Increased system capacity

All electrical distribution systems are rms current limited. Harmonic currents carried by transformers, switchgear, and wiring use up system capacity that could be used to carry 60 Hz currents that do work. By eliminating 3rd harmonic currents throughout the entire distribution system, the HSS provides the facility with more useful capacity without requiring that the electrical system be upsized.

Greater reliability

The major cause of failure for transformers and equipment is overheating. Random breaker tripping due to harmonic heating is well known. The elimination of 3rd harmonic currents reduces heat in all parts of the distribution system, thereby reducing the likelihood that system components will fail or trip off due to excessive temperatures. The elimination of high neutral currents lowers neutral-to-ground voltages and reduces the likelihood that data errors will occur.

Energy and Operating Cost Savings

Excessive heat in electrical distribution systems means wasted energy. The heat is due to I2R losses in all system components, and appears directly in energy bills as increased kW hour charges. Installation of the HSS eliminates this wasted energy and leads to a direct reduction in energy costs. A recent study showed that, depending on transformer loading and the distribution distance from the transformer, the energy saved by eliminating 3rd harmonic currents ranged from a minimum of 2.5 percent to a maximum of 8 percent of the energy used to power computers.10 A graph from this study is shown as figure 5 shows. In addition to the direct waste of energy caused by harmonic currents, there is a secondary effect. Air conditioners must be powered to remove this excess heat. Reducing extra operation of air conditioners, necessary because of harmonic generated heat, can add another 1–3 percent to the energy saved by an HSS. The bottom line is that the installation of an HSS can pay for itself in two to three years.

Conclusions

The harmonic suppression system is a well established technology. It has been on the market for more than 10 years without a single documented case of damage to equipment in any facility. It has been embraced by a wide variety of users, including major computer manufacturers, banks, stock exchanges, educational institutions, insurance companies, broadcast facilities…in short any group that uses multiple computers. The capacity and energy savings are well documented and life safety and reliability issues need no longer be of concern to users. It would be unfortunate if some were deterred from using this innovative and effective technology by undocumented allegations and suggestions of "potential" problems that are never realized in the real world.

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Dr. Lowenstein holds an A.B. in chemistry from Oberlin College, and an M.S. and Ph.D. in physical and analytical chemistry and physics from Arizona State University. He spent 13 years as a college chemistry professor and 8 years as a national program manager for the Solar Energy Research Institute. His experience with harmonics includes 15 years designing filters for 3-phase industrial drives. In 1989 he founded Harmonics Limited, a company devoted to solving harmonic problems caused by multiple computer loads.

He has served as a lecturer at the University of Wisconsin, Milwaukee, teaching courses in power quality and non-linear loads. He has presented invited lectures and seminars at national meetings for numerous organizations with concerns about power quality and harmonics.

Dr. Lowenstein is a member of The IEEE Industrial Applications Society, The Power Engineering Society, and the Standards Society. He serves on SCC 22, the power quality Standards Coordination Committee, the body with coordination responsibility for all IEEE power quality standards, and is involved in the revision of IEE519 currently underway.

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Figure 1.

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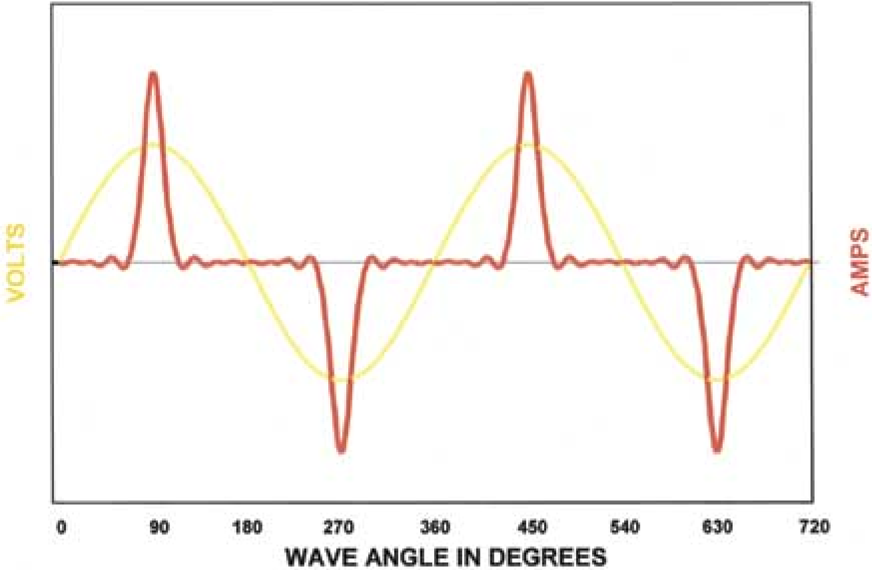

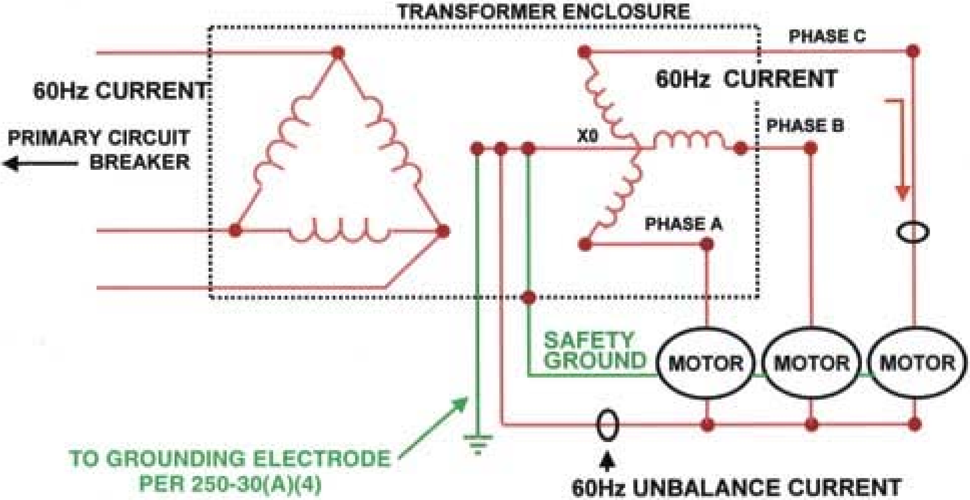

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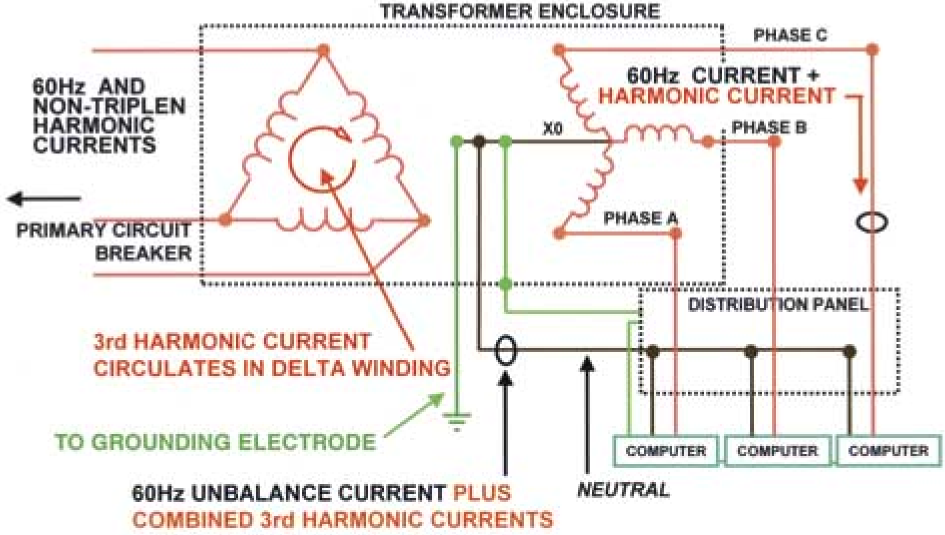

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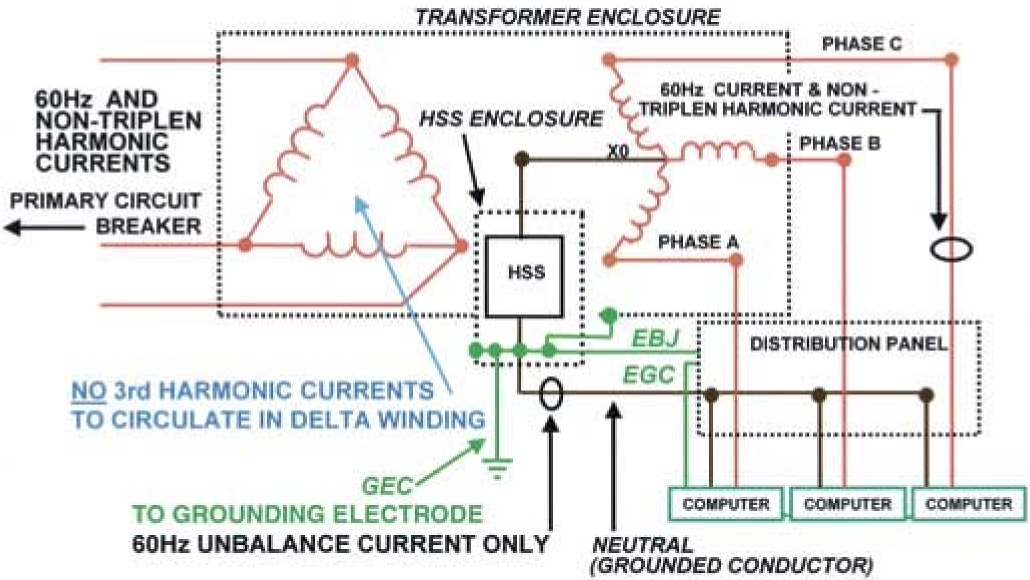

Figure 4.

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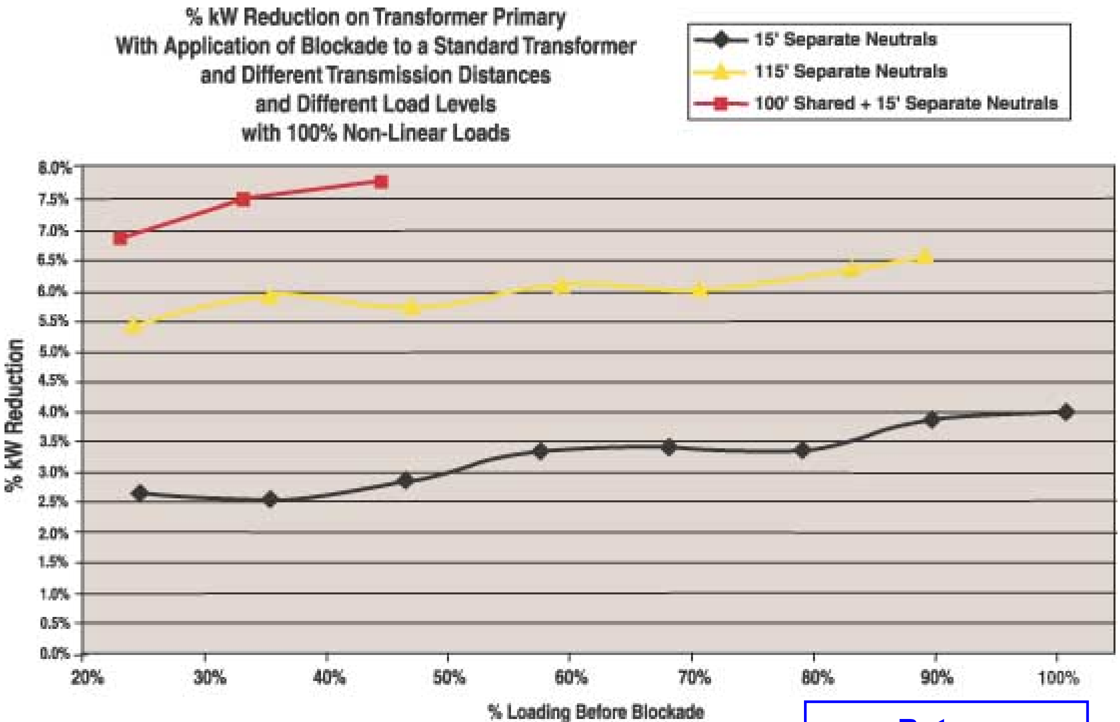

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Figure 5.