An examination of the "lifted neutral" phenomenon

UL and CSA have implemented test methods and specifications to prevent a SPD from violent failure when exposed to a "lifted neutral" event.

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Within the last five years there has been much debate within power quality circles regarding the operation of surge protection devices (SPDs) when exposed to a "lifted neutral" phenomenon. A "lifted neutral" event occurs when the neutral conductor has been removed, either deliberately or accidentally, from a split-phase or 3-phase wye configuration. This debate is evident by the incorporation of the abnormal overvoltage; limited current test (ABOV-LC) defined by the Underwriters Laboratories Inc. *Standard for Safety, Transient Voltage Surge Suppressors.*[1]

However, this debate has just begun. SPD manufacturers are not only at odds over the probability of such an event, but also the severity of the event if it should occur. There are additional debates over whether or not differences occur between permanently-connected SPDs and cord-connected or direct plug-in SPDs. To make matters worse, no mathematical studies or computer simulations have been published for scientific analysis. Additionally, no reports have been published concerning an actual "lifted neutral" event.

It could be possible to explain the absence of technical publications to the extremely low probability of a "lifted neutral" event occurring. This explanation, however, does not explain why UL and Canadian Standards Accociation (CSA) have implemented various test methods and specifications to prevent a SPD from violent failure when exposed to a "lifted neutral" event.

To determine the actual probability of the "lifted neutral" event occurring in a facility, one only has to look at the speed with which UL and CSA implemented the specifications and test methods for this event. Examination of the UL standard and their actions show that representative samples of all existing products along with any future products must meet the new specifications by the February 1998 implementation date. Therefore, it is reasonable to conclude that a "lifted neutral" event has a high probability of occurring in both permanently-connected and cord-connected or direct plug-in SPDs.

SAFETY AGENCY REQUIREMENTS

The test requirements as described in the UL standard are virtually the same for permanently-connected and cord-connected or direct plug-in SPDs. The standard requires that representative samples be subjected to the ABOV-LC test for a period of seven hours. The voltage is applied to each primary mode of operation of a split-phase or 3-phase wye SPD: line-to-neutral, line-to-ground, and neutral-to-ground. The voltage applied is determined by the maximum voltage available from the source and is shown in Table 1. The short circuit current limitations are 5.0 amperes, 2.5 amperes, 0.5 amperes, and 0.125 amperes.

For example, if a SPD were connected to 120/208-volt, 3-phase wye in the line-to-neutral configuration, the applied overvoltage condition would be 208 volts. The first representative sample would be subjected to a limited current of 5.0 amperes. If the product contains devices or circuitry that will take the unit off-line before the end of the 7 hours, limited current testing must continue at the 2.5 ampere level. This scenario is repeated until the representative samples of the SPD complete the 7-hour test or until all four limited current values have been tested.

The ABOV-LC test sequence is performed on three representative samples in all previously mentioned modes of operation. At the conclusion of the ABOV-LC test, all permanently connected SPDs must complete the Grounding Continuity Test as detailed in the UL standard.

The test requirements for a cord-connected and a direct plug-in SPD are more stringent. These devices must successfully complete the Leakage Current Test and Dielectric Withstand Test as outlined in the UL standard.

During and following the overvoltage, limited current test, the representative samples of the SPD can not 1) emit flame, molten metal, glowing or flaming particles through an opening whether pre-existing or caused as a result of the test, 2) show evidence of charring, glowing, or flaming of the supporting soft wood surface and/or tissue paper and the encompassing cheesecloth, 3) ignite the enclosure, or 4) create any openings in the enclosure that would result in the accessibility of live parts.

ROOT CAUSES OF A "LIFTED NEUTRAL" PHENOMENON

A "lifted neutral" event is only possible in a 3-phase wye configuration or a split-phase configuration where the impedance of the neutral conductor exceeds the impedance level required to allow unbalanced load current to flow back to the source. Practically speaking, the neutral-to-ground bond is no longer applicable due to corrosion or an open neutral conductor.

Corrosion of the neutral-to-ground bond can occur when the bond is made using dissimilar metals. One example is the utilization of copper conductors that are joined with copper-plated lugs which utilize standard steel set-screws for tightening purposes. Another example is when copper conductors are joined with aluminum conductors. These examples may appear generally harmless. However, factors relating to the pH balance of any solution coming in contact with the dissimilar metals or the presence of salt in water, air, or mist can accelerate the oxidation process, thereby increasing the amount of corrosion and the resistance of the neutral-to-ground bound.

If the probability of a "lifted neutral" conductor due to corrosion is extremely small, an explanation of the "lifted neutral" scenario must exist. Three possible root causes are 1) carelessness, 2) creepage of conductor lugs, and 3) the opening of an undersized neutral conductor itself. The first root cause, carelessness, can be prevented and avoided by the utilization of educated and dedicated employees who strictly follow all local and national electrical codes along with a good quality assurance program.

The second root cause, creepage of conductor lugs, may occur over an extended period of time when the lug utilized to secure the neutral-to-ground bond actually loosens. This is due to the expansion and compression of the conductors in the lug itself.

CONDUCTOR CHARACTERISTICS

The third root cause, an open neutral due to an improperly sized conductor, is harder to recognize and evaluate. All conductors are composed of inherent characteristics such as resistance, inductance,

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Voltage Rating (VAC)	Phase Configuration	Test Voltage (VAC)
110-120	Single	240
110-120/220-240	Split	240
120/208	3-wye	208
220-240	Single	415
220-240/380-415	3-wye	415
254-277	Single	480
254-277/440-480	3-wye	480
347	Single	600
347/600	3-wye	600

Table 1. Abnormal overvoltage limited current test voltage and phase configuration matrix as defined by UL's* "Standard for Safety, Transient Voltage Surge Suppressors," *UL 1449, Second Edition, page 69, 15 August 1996.

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capacitance and conductance. Of these characteristics, the most important for a facility neutral conductor is resistance. It is of little significance whether the series facility neutral conductor has an extra inductance of a few micro-henries or an extra capacitance of a few nano-farads. Conductance, in general, is not even an issue at low frequencies. It is extremely important, however, if the neutral conductor has an extra resistance of a few ohms.

The resistance *R* of a neutral conductor is calculated by:

$$R = \frac{\ell}{\sigma * \pi * r^2} \qquad (1)$$

where ℓ is the length of the conductor, σ is the conductivity of the conductor (5.8×10^7 S/m for copper), and *r* is the radius of the conductor.

As a copper atom absorbs thermal energy, its electrical resistance increases. This increase in resistance hinders the flow of current in the conductor. To determine the resistance of the conductor while taking into account variations in temperature, the equation becomes:

$$R = \frac{dR}{dT}\left(\frac{\ell}{\sigma * \pi * r^2}\right) \qquad (2)$$

where *dR/dT* is the change in resistance due to the change in temperature (positive as temperature increases).

As shown in Equation 2, the resistance of a conductor increases with temperature. However, to add large amounts of thermal energy, power must be consumed in the conductor. The standard power equation for any resistive element is:

$$P = I^2 R \qquad (3)$$

where *P* is the power in watts, *I* is the current through the conductor in amperes, and *R* is the resistance of the conductor in ohms.

As previously mentioned, one of the ways that a neutral conductor can open is an undersized conductor. If the current flowing through the neutral conductor is in excess of its rated load, the power dissipated in the conductor will increase. See Table 1 for recommended currents for the applicable conductor size. When combing Equation 2 and Equation 3, the power equation for a conductor becomes:

$$P = I^2 \frac{dR}{dT}\left(\frac{\ell}{\sigma * \pi * r^2}\right) \qquad (4)$$

It is now evident that as the resistance starts to increase in an undersized conductor, the power also increases. This, in turn, increases the resistance of the neutral conductor. This scenario will continue until thermal equilibrium occurs in the neutral conductor.

Wire Size (AWG or kcmil)	Maximum Current w/a Conductor Rated at 60° C (amperes)
250	205
4/0	187
3/0	158
2/0	138
1/0	121
1	102
2	88
3	76
4	66
6	48
8	36
10	27
12	20
14	16

Table 2. Ampacities of two or three insulated conductors, rated 0 through 2000 volts, within an overall covering, in raceway in free air based on ambient air temperature of 30° C as described by the National Electrical Code (NEC).[2]

So far we have examined the effects of resistance as it changes with temperature. To complete our examination, we must also define the current flowing through the conductor. The total current in a facility power grid must take into account any harmonic frequencies, which may be developed by the equipment utilized in the facility. Harmonics can be defined as the additive partials of the fundamental current.

The total current in the neutral conductor, taking into account any harmonic frequencies, is represented by:

$$I = \sqrt{I_1^2 + I_2^2 + I_3^2 + \cdots + I_n^2} \qquad (5)$$

where I_1 is the fundamental frequency (60 hertz), I_2 is the second harmonic frequency (120 hertz), I_3 is the third harmonic frequency (180 hertz), and so forth.

When Equation 4 and Equation 5 are combined, an under-sized neutral conductor which was not designed to take into the account the effects of applied harmonics or the thermal properties of the conductor, will open causing a "lifted neutral" condition.

ANALYSIS OF THE "LIFTED NEUTRAL"

As previously stated, a "lifted neutral" phenomenon can occur within a facility, but only within a 3-phase wye or a split-phase configured system. However, the question remains concerning the severity of this condition. When the neutral conductor is in the circuit, any current from an unbalanced load will return to the source via this conductor. The problem is when there is no neutral conductor to return this

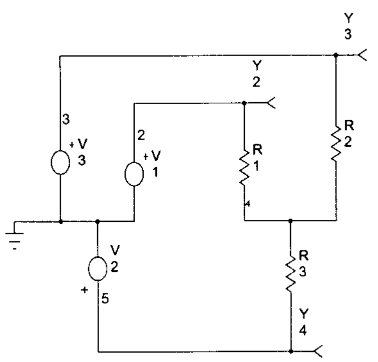

Figure 1. Schematic representation of a 120/208-volt 3-phase wye system configured with a "lifted neutral" connection.

unbalanced load current.

Figure 1 shows a simplified model of a 3-phase wye power source and a 3-phase wye load without the neutral conductor connected, where Z1, Z2, and Z3 can be substituted for R1, R2, and R3 respectively. The voltage between Phase A and Phase B, denoted as V_{AB}, is determined by:

$$V_{AB} = I_{AN} Z_1 - I_{BN} Z_2 \qquad (6)$$

where I_{AN} is the current from Phase A to neutral; Z_1 is the load impedance of Phase A; I_{BN} is the current from Phase B to neutral; and Z_2 is the load impedance of Phase B. The same relationships can be derived for the voltages between Phase B and Phase C, V_{BC}, and the voltages between Phase C and Phase A, V_{CA}, by:

$$V_{BC} = I_{BN} Z_2 - I_{CN} Z_3 \qquad (7)$$

$$V_{CA} = I_{CN} Z_3 - I_{AN} Z_1 \qquad (8)$$

where I_{BN} is the current between Phase B and neutral; I_{CN} is the current between Phase C and neutral; Z_2 is the load impedance of Phase B; and Z_3 is the load impedance of Phase C. Since the source can only develop a finite amount of current, and the summation of all the phase currents equals zero, then mathematically we say:

$$I_{AN} + I_{BN} + I_{CN} = 0 \qquad (9)$$

Rearranging Equation 9 yields:

$$I_{BN} = - I_{AN} - I_{CN} \qquad (10)$$

Substituting Equation 10 into Equation 6, Equation 7, and Equation 8 and solving for the respective phase-to-neutral currents using determinates, yields the following phase-to-neutral current equations:

$$I_{AN} = \frac{V_{AB} Z_3 - V_{CA} Z_2}{Z_1 Z_2 + Z_1 Z_3 + Z_2 Z_3} \qquad (11)$$

$$I_{BN} = \frac{V_{BC} Z_1 - V_{AB} Z_3}{Z_1 Z_2 + Z_1 Z_3 + Z_2 Z_3} \qquad (12)$$

$$I_{CN} = \frac{V_{CA} Z_1 - V_{BC} Z_3}{Z_1 Z_2 + Z_1 Z_3 + Z_2 Z_3} \qquad (13)$$

With these phase-to-neutral equations derived for Phase A, Phase B, and Phase C, the final step is to calculate the relative phase to neutral voltages. This is accomplished by using Ohm's Law ($V = I \cdot Z$). However, before this is accomplished, it is important to note that the voltages and currents are vector quantities. As such, it is important to utilize these equations using the magnitude and phase quantities of each value.

A mathematical simulation was performed using *MathCAD* by *Mathsoft* to determine the voltages across the various loads with the neutral conductor removed. The resulting peak voltages were obtained and are contained in Table 3. To verify the mathematical equations, a computer simulation was performed using *IsSpice* from *Intusoft* with various resistive load impedances. The simulations and calculations were performed on a 120/208-volt, 3-phase wye system with a maximum source current of 100 amperes per phase. The frequency of the system was 60 hertz.

Data was obtained for load impedances ranging from a 100% load to a 10% load. The resulting peak voltages and currents obtained are shown in Table 3. Graphical data of a simulation which utilized a 100% load on Phase A, a 75% load on Phase B, and a 10% load on Phase C is shown in Figure 2.

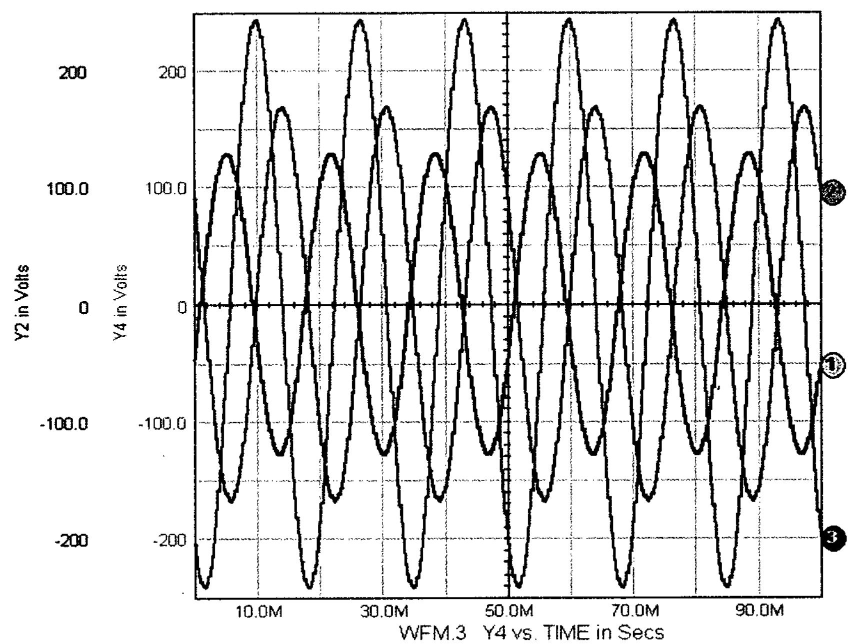

Figure 2. Computer simulation of the phase-to-neutral voltages of a 120/208-volt, 3-phase wye system configured for a "lifted neutral" event. Phase A (1) current at 100 amperes (100%), phase B (2) current at 75 amperes (75%), and phase C (3) current at 10 amperes (10%).

Parameters	Comparison No. 1	Comparison No. 2	Comparison No. 3	Comparison No. 4	Comparison No. 5
Z_1	1.2 Ω (100%)	1.2 Ω (100%)	1.2 Ω (100%)	1.2 Ω (100%)	1.2 Ω (100%)
Z_2	1.6 Ω (75%)	1.6 Ω (75%)	1.6 Ω (75%)	1.6 Ω (75%)	1.6 Ω (75%)
Z_3	1.6 Ω (75%)	2.0 Ω (60%)	3.0 Ω (40%)	4.0 Ω (30%)	12.0 Ω (10%)
Simulated V_A (pk)	154	148	140	136	128
Simulated V_B (pk)	179	175	171	169	168
Simulated V_C (pk)	179	190	206	216	242
Calculated V_A (pk)	153	147	139	135	128
Calculated V_B (pk)	179	175	171	169	168
Calculated V_C (pk)	179	191	208	218	242
Calculated I_A (pk)	128	122	115	112	106
Calculated I_B (pk)	112	110	107	106	105
Calculated I_C (pk)	112	95	69	55	20

Table 3. Comparison matrix between the computer simulated model and the mathematical model of the overvoltage condition of a 120/208-volt 3-phase wye configuration.

CONCLUSION

The data in Table 3 shows that the computer simulation and the mathematical model are in good agreement. It is also evident that as the impedance of all loads are mismatched between the three phases, the voltage also becomes mismatched, with the highest voltage on the highest impedance phase. The data also shows the voltage decreases on the phase with the lowest impedance. This makes sense as Ohm's Law is preserved.

This analysis was performed using a 120/208-volt, 3-phase wye, 100-ampere service. If the service changed to 500 amperes, the current data shown in Table 3 would increase five times. If the service was increased to 1000 amperes, the currents listed in Table 3 would increase ten times. To illustrate, a 1000-ampere service configuration with an unbalanced configuration of 100% on Phase A, 75% on Phase B, and 10% Phase C, would yield voltage and currents of 128 volts at 1060 amperes, 168 volts at 1050 amperes, and 242 volts at 200 amperes, respectively. This result is in conflict with the limited current test requirements stated by UL, which utilizes limited currents of 5.0 amperes, 2.5 amperes, 0.5 amperes, and 0.125 amperes.

Since it would be impossible for a SPD to attenuate any significant amount of the available limited current when connected to large power grids, all devices would be exposed to these voltages. However, with the limited current levels described in UL 1449, five amperes and below, a minimum level of safety can be assumed by products which have been evaluated to this test procedure. It is, therefore, reasonable to have all devices, not just SPDs, connected to the power grid and evaluated to the limited current test procedure described in UL 1449, preferably at current levels defined by the intended application.

In conclusion, a mathematical model and a computer simulation technique has been presented for the analysis of a "lifted neutral" event. Additionally, four probable causes of the open neutral have been presented: corrosion, carelessness, the creepage of connections over time, and an opened neutral because of an over-current condition. These items, along with the speed with which UL incorporated the abnormal overvoltage, limited current specifications and test methods into the second edition of UL 1449, and required pre-existing products and all new products, clearly shows that the "lifted neutral" phenomenon is a relevant problem with a high probability of occurring. These facts should spark the manufacturers and end-users of SPDs, as well as manufacturers of other equipment connected to the power grid, to develop and demand products which can demonstrate not only the higher levels of performance, but first and foremost, safety.

REFERENCES:

1. Underwriters Laboratories, Inc., *Standard for Safety, Transient Voltage*

Surge Suppressors, UL 1449, Second Edition, 15 August 1996.

2. National Electric Code, *National Electric Code Handbook*, 1996, Appendix B, Table B-310-1, page 910.

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