Data Center Energy White Paper 04 — Causes of Generation of Neutral-ground Voltage and Related Misunderstandings

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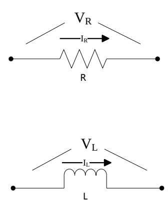
Preface

For data centers, disputes about the neutral-ground voltage never stop. Server vendors and data center maintenance personnel think that the neutral-ground voltage greatly influences normal operations of data centers' devices and the neutral-ground voltage of data centers needs to be controlled below 2 V and even below 1 V. They draw such a conclusion based on cases. They believe that servers of data centers' devices easily break down, telecommunication devices run slowly, and the communication speed slows down when the neutral-ground voltage is high and above problems are resolved after the neutral-ground voltage decreases to a reasonable level. However, power supply device vendors and experts think that the neutral-ground voltage has no direct influences on data centers' devices and what only needs to be done is to control the neutral-ground voltage below 10 V. They draw such a conclusion based through deduction based on the circuit logic. They believe that there is no path for the neutral-ground voltage to influence loads. Based on research results of predecessors, I tried finding the relationship between the neutral-ground voltage and data centers' devices and giving suggestions accordingly.

1. What Causes the Generation of the Neutral-ground Voltage?

Before I explain what causes the generation of the neutral-ground voltage, I need to introduce influences of wire impedance on high-frequency currents and low-frequency currents.

Figure 1 Wire resistance and inductive reactance



Take a 200 kHz UPS whose switching frequency is 6 kHz as an example. Its phase current is 300 A and it uses AWG 3/0 cables for input. The usual length of AWG 3/0 cables is 50 m. As the diameter of the N wire and PE wire doubles, N wire's resistance is 0.0021 Ω and its inductive reactance is about 10 uH. To simplify mathematical operation, the power-frequency current, power-frequency voltage, and power-frequency impedance are decoupled from the high-frequency current, high-frequency voltage, and high-frequency impedance. According to table 1, we can see that, if the current is of the power frequency, 476 A is required for realizing 1 V power-frequency voltage drop on N wire. If the intensity of the power-frequency current on N wire is 1/3 of that of the phase current, that is, 100 A, only 0.2 V voltage drop is realized. If the current on N wire is the 24 kHz high-frequency current, only 660 mA is required for realizing 1 V high-frequency voltage drop.

Table 1 Influences of wire impedance on high-frequency currents and low-frequency currents

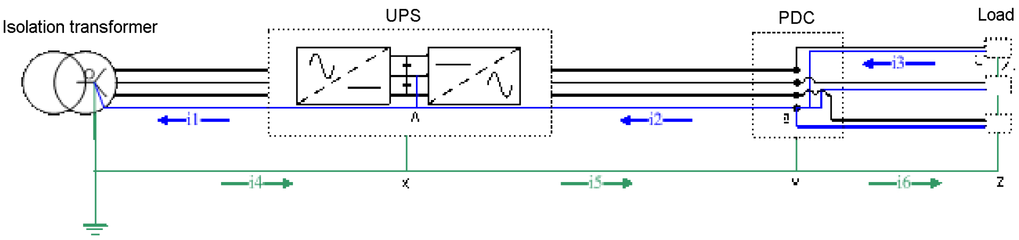
	R (0.0021 Ω)	L (10 uH)	When There Is Only Wire Resistance R, IR(A) Current Is Needed for 1 V Voltage Drop	When There Is Only Inductive Reactance L, IL(A) Current Is Needed for 1 V Voltage Drop
DC	0.0021	6.28319E-05	476.1904762	-
50 Hz power-frequency current	0.0021	0.003141593	476.1904762	318.3098862
150 Hz third harmonic current	0.0021	0.009424778	476.1904762	106.1032954
250 Hz fifth harmonic current	0.0021	0.015707963	476.1904762	63.66197724
6 kHz high-frequency current	0.0021	0.376991118	476.1904762	2.652582385
12 kHz high-frequency current	0.0021	0.753982237	476.1904762	1.326291192
18 kHz high-frequency	0.0021	1.130973355	476.1904762	0.884194128

	R (0.0021 Ω)	L (10 uH)	When There Is Only Wire Resistance R, IR(A) Current Is Needed for 1 V Voltage Drop	When There Is Only Inductive Reactance L, IL(A) Current Is Needed for 1 V Voltage Drop
current				
24 kHz high-frequency current	0.0021	1.507964474	476.1904762	0.663145596

According to calculation results in the above table (assume that connection is standard), we can see that, the power-frequency current on N wire whose intensity is lower than 1/3 of that of the phase current or the third harmonic current on N wire whose intensity is lower than 1/10 of that of the phase current has a little influence on the wire voltage drop, which can be ignored. However, high-frequency currents with the switching frequency or with the frequency that is multiple times as high as the switching frequency have great influences on the wire voltage drop even when their intensity is low.

In the following, the UPS neutral-ground voltage in the TN-S system is analyzed.

Figure 2 UPS neutral-ground voltage in the TN-S system



RAO, RBA, and RCB are impedance of OA, AB, and BC segments of N wire (neutral wire) separately.

ROX, RXY, and RYZ are impedance of OX, XY, and YZ segments of PE wire (ground wire) separately.

VAO=i1*RAO VBA=i2*RBA VCB=i3*RCB

VOX=i4*ROX VXY=i5*RXY VYZ=i6*RYZ

The neutral-ground voltage on the load side VCZ = VAO + VBA + VCB + VOX + VXY + VYZ

= i1*RAO + i2*RBA + i3*RCB + i4*ROX + i5*RXY + i6*RYZ

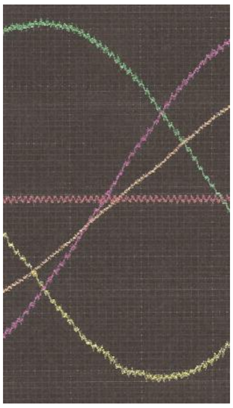
We can see that, the neutral-ground voltage on the load side is related to impedance and currents of the neutral wire and ground wire. Details are introduced in the following.

(1) OA Segment

i1 indicates currents from the isolation transformer to the UPS on N wire, including power-frequency currents formed on N wire due to imbalance between three-phase input currents and high-frequency currents formed on N wire by three-phase high-frequency ripple currents. At present, three-phase input currents of the three-phase UPS are usually balanced. The intensity of power-frequency currents is very low, lower than 5% of the intensity of phase currents. Therefore, power-frequency currents on N wire have a little influence on the voltage drop on N wire, which can be ignored. However, influences of high-frequency currents cannot be ignored. For UPS inputs, high-frequency currents on N wire are the main factor that influences the voltage drop on N wire.

Figure 3 shows the input currents of a transformer-less UPS. The waveform is sinusoidal. The wave of ripples with the switching frequency is shown. These ripples cannot be offset by three-phase high-frequency ripples, which causes the formation of high-frequency currents on N wire.

Figure 3 Input currents of a UPS



(2) AB Segment

i2 indicates third harmonic currents and power-frequency & high-frequency currents on N wire output by the UPS. Influences of high-frequency currents on the voltage drop on N wire cannot be ignored. As for influences of power-frequency currents and third harmonic currents, see the 200 kHz UPS example. When loads of three phases are imbalanced, the intensity of power-frequency currents on N wire can be as high as that of the phase current to the maximum extent, that is, 300 A. With the non-linear load, the intensity of third harmonic currents on N wire can be two times as high as that of the phase current, about 600 A. We can see that both power-frequency currents and third harmonic currents on N wire output by the UPS have influences on the voltage drop on N wire. In other words, for the AB segment, both power-frequency currents (including third harmonic currents) and high-frequency currents on N wire have great influences on the voltage drop on N wire.

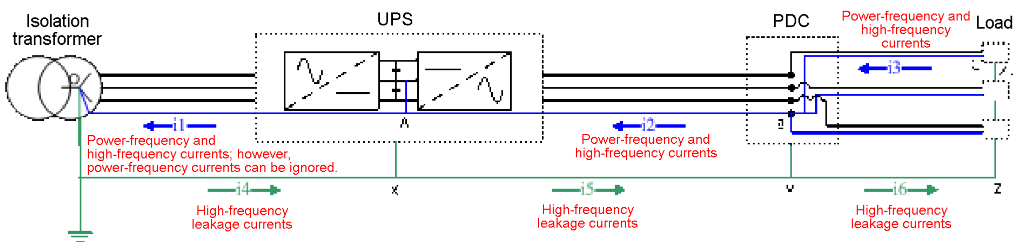
(3) BC Segment

The intensity of power-frequency currents on the BC segment of N wire is equal to that of the phase current. Therefore, the situation on the BC segment is similar to that on the AB segment. Both power-frequency currents and high-frequency currents on N wire have great influences on the voltage drop on N wire.

(4) OX, XY, and YZ Segments

i4, i5, and i6 indicate Y capacitor currents and other leakage currents on PE wire in the UPS and ICT device. Security regulations usually require that the intensity of power supply leakage currents shall be lower than 3.5 mA. However, most of power supplies are devices with leakage currents whose intensity is higher than 3.5 mA and even reaches above 1 A in operations. Most of aforesaid currents are high-frequency currents. The voltage drop on OX, XY, and YZ segments of the ground wire are mainly caused by high-frequency leakage currents.

Figure 4 Causes of the generation of the neutral-ground voltage



After analysis in the above, I drew the above figure, to show what causes the generation of the neutral-ground voltage. According to the figure, we can see that i1 to i6 currents and corresponding wire impedance cause the generation of the neutral-ground voltage.

2. Influences of the Neutral-ground Voltage on ICT Devices

Too high neutral-ground voltage threats loaded EMI circuits to a certain extent and may lead to burn-out of EMI circuits. This may happen when the neutral-ground voltage is high enough to break through Y capacitor. Then, whether the neutral-ground voltage below 20 V has influences on ICT loads?

Figure 5 Influences of power supply input ripple currents on ICT loads

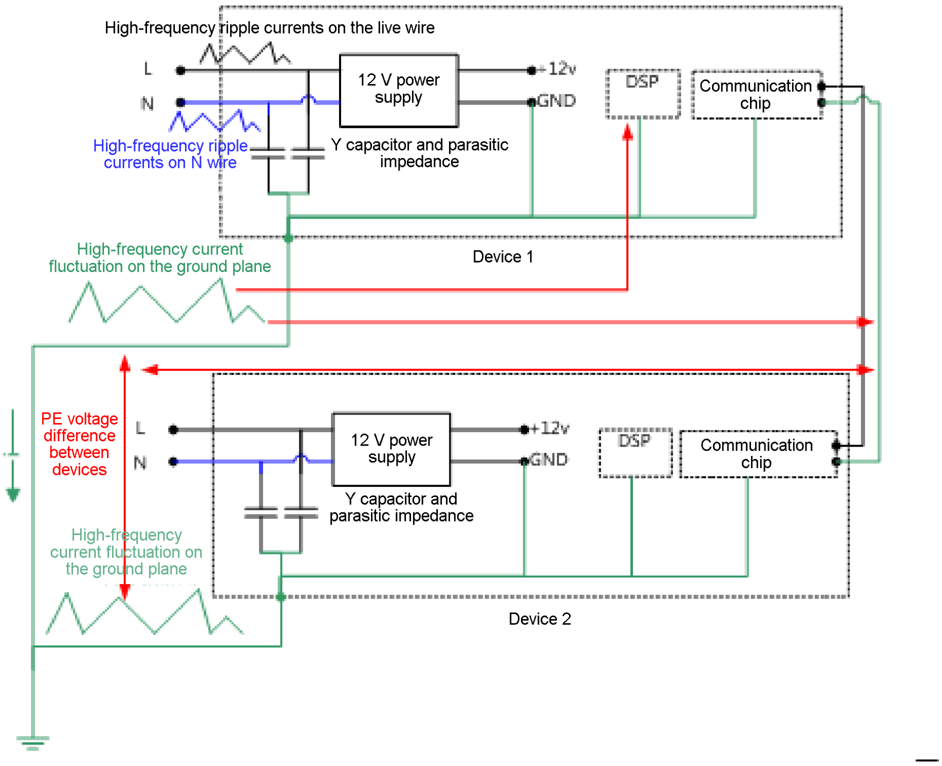


Figure 5 shows the general situation of ICT devices. In the actual situation, with the consideration of immunity to interference and EMC, 12 V reference ground of most of ICT power supplies is grounded (PE). Due to this, PE interference influences ICT devices. As shown in the figure, high-frequency ripple currents on the live wire and N wire are coupled to ground planes through Y capacitor and parasitic impedance. As ground planes on which devices are put have certain inductive reactance, they can perceive interference of high-frequency currents. The interference influences DSP and communication wires: DSP easily breaks down and the communication bit error rate increases. In addition, the ground plane between the two devices also has certain inductive reactance. As a result, different high-frequency currents between the two devices cause the ground wire voltage difference between them, which will lead to ground wire cross currents and influence communication wires.

What needs attention is that the fluctuation of power-frequency currents on ground planes has a little influence on ICT devices, as ground planes are raised floors in most of ICT data centers. The resistance (corresponding power-frequency impedance) is very small. However, the parasitic inductance is related to the area surrounded by circuits and has great influences on high-frequency currents when it reaches uH. Therefore, in figure 4, only the fluctuation of i5 and i6 high-frequency currents has a certain influence on ICT devices. The neutral-ground voltage generated by i1 to i4 currents has nearly no influence on ICT devices.

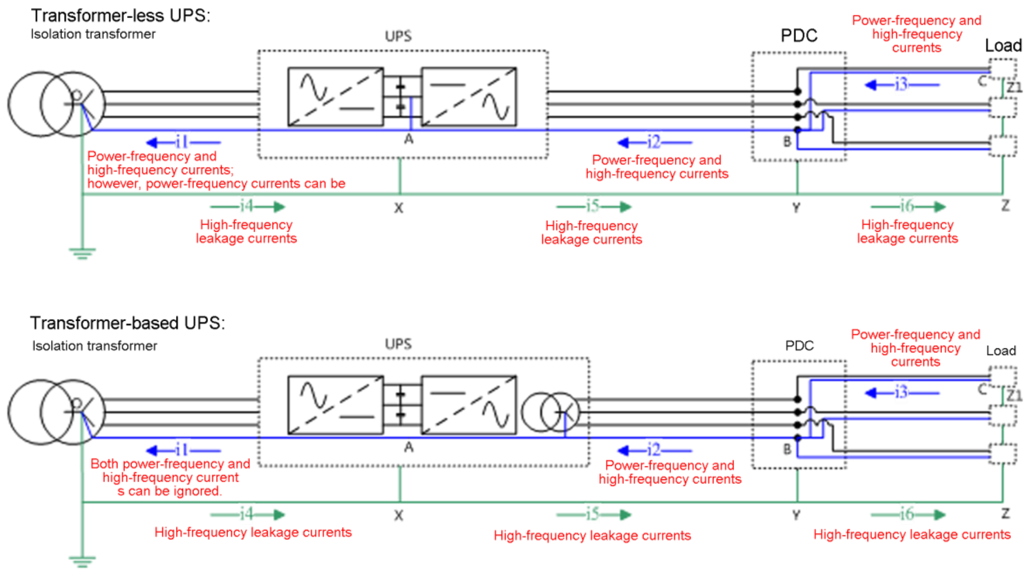
3. Comparison of Influences of Transformer-less UPS's and Transformer-based UPS's Neutral-ground Voltage on ICT Devices

According to analysis in the preceding part, only the fluctuation of i5 and i6 high-frequency currents has a certain influence on ICT devices in the system shown by figure 5. Then, what are differences between transformer-based UPSs and transformer-less UPSs in terms of the neutral-ground voltage?

According to figure 6, we can see that a transformer-based UPS has the isolation transformer. The input N connects to the neutral point of the isolation transformer. In this way, the output N does not include power-frequency and high-frequency currents. (Actually, high-frequency currents of the output N of the UPS are still coupled to the input N. However, as there are so few currents coupled. We can ignore them.) The neutral-ground voltage in other positions is the same as that of the transformer-less UPS. The neutral-ground voltage of a transformer-based UPS is mainly determined by i2 to i6 currents and corresponding wire impedance. While the neutral-ground voltage of a transformer-less UPS is determined by i1 to i6 currents and corresponding wire impedance. With the same conditions, measurement results show that the neutral-ground voltage of most of transformer-based UPSs is lower than that of transformer-less UPSs, especially when measurement points are A and X.

According to the conclusion in the above, the neutral-ground voltage does not directly influence ICT loads. As shown in figure 6, only i5 and i6 currents influence normal operations of ICT devices. As i5 and i6 currents and wire impedance of transformer-based UPSs and transformer-less UPSs are the same, influences of transformer-based UPSs and transformer-less UPSs on ICT loads are the same.

Figure 6 Difference in the neutral-ground voltage between the transformer-less UPS and the transformer-based UPS



High-frequency ripples on the output wire (the input wire of the load power supply) of UPSs have direct influences on i5 and i6. Some transformer-less UPS vendors produce UPSs with the small filter inductor to reduce costs. As a result, high-frequency ripples of output voltage are not completely filtered out, which causes the interference problem of transformer-less UPSs in data centers. Transformer-based UPSs use the output isolation transformer's leakage inductance as the filter inductor and also has such a problem. Based on all these, we can draw the conclusion that influences of the transformer-based UPS's and the transformer-less UPS's neutral-ground voltage on data centers are the same.

4. Relationship Between Power Distribution System and Neutral-power

Voltage

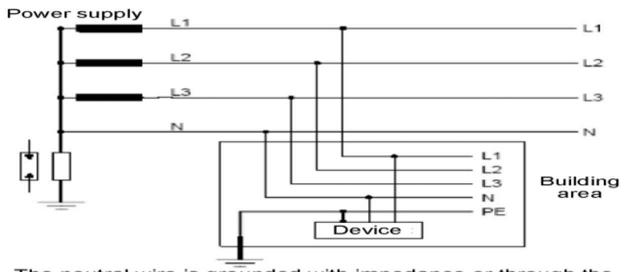
The aforesaid analysis is conducted based on the TN-S system, which is the most common in China's data centers. In the actual situation, countries outside China or some provincial authorities in China use other power distribution systems. No matter which power distribution system is used, causes of the generation of the neutral-ground voltage and influences of the voltage are the same.

According to IEC and GB definitions, there are five power distribution systems, IT, TT, TN-C, TN-S, and TN-C-S. Among these systems, TN-C-S is the complex of TN-C and TN-S. Therefore, analysis will not be separately conducted for it.

a. IT System

In the IT system, the UPS shell is directly grounded, while the neutral point of the power supply is not grounded or is grounded with high impedance. You are advised not to set the neutral, as several or a dozen V neutral-ground voltage is generated due to the high impedance between N and PE of an IT system with the neutral.

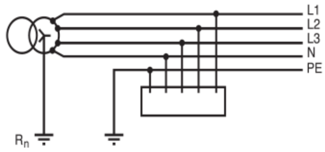
Figure 7 IT system



b. TT System

In the TT system, the neutral point of the power supply is grounded, and the UPS shell is also grounded. There are no electrical connections between two grounding points. In China, many small telecommunication authorities use such a system. In the actual situation, the UPS shell is not grounded in a standard manner or reliably. The neutral-ground voltage of the UPS reaches dozens of or even a hundred V. Though the neutral-ground voltage is so high, the UPS runs normally. However, the risk that EMC circuits may be damaged exists.

Figure 8 TT system

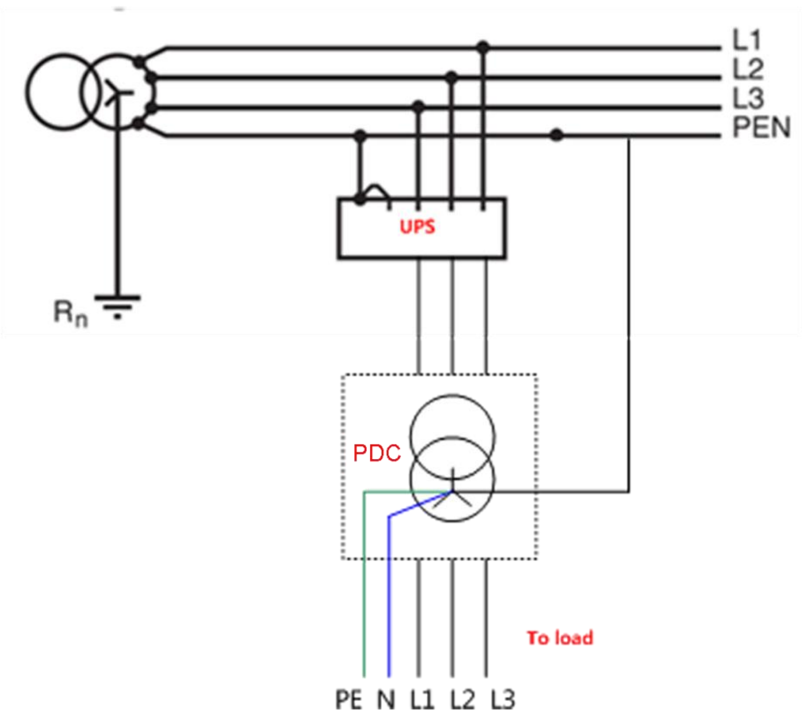


In the TN-C system, N and PE use the same wire. Therefore, the neutral-ground voltage is zero.

In North America, most of data centers use the 480 V TN-C system. As the load of data centers is 120 V single-phase power input, the step-down isolation transformer needs to be configured to the power distribution cabinet (PDC). The isolation transformer changes the TN-C system into the TN-S system. In such an architecture, as the load is near the isolation transformer, the neutral-ground voltage problem usually does not occur.

The TN-S system is the most common in data centers of China. Specific analysis has been conducted before. No more information is introduced here.

Figure 9 TN-C system



5. Misunderstandings About Neutral-ground Voltage and Suggestions

After analysis, we can see that misunderstandings about the neutral-ground voltage exist in the present.

Misunderstanding 1: Take the neutral-ground voltage as a standard indicator to determine the influence of the UPS on devices. Actually, the neutral-ground voltage is determined by neutral-ground currents and impedance before and after the UPS input. Only currents and corresponding impedance on the ground wire after the UPS input have influences on the load. The neutral-ground voltage can be taken as a reference. However, it is unscientific to take the neutral-ground voltage as a standard indicator to determine the influence of the UPS on devices. In addition, different power distribution systems have different neutral-ground voltages. For example, the IT system itself has the neutral-ground voltage. However, its neutral-ground voltage has no influences on data centers. The neutral-ground voltage generated by the neutral wire and ground wire on the input side of the power distribution system and the UPS has a little influence. UPS and devices run normally if the neutral-ground voltage is below 10 V.

Misunderstanding 2: Transformer-based UPSs have a small neutral-ground voltage and a little influence on data centers. Actually, transformer-based UPSs and transformer-less UPSs have no differences in terms of high-frequency currents on the ground plane that influence the load. At present, the neutral-ground voltage of most of transformer-less UPSs is below 2 V.

For data centers, in the *Analysis of Influences of Neutral-ground Voltage on Data Communication Devices*, joint experiment results of Huawei and China Telecom show that servers and telecommunication devices can resist interference of above 2.5 V ground voltage and interference of above 15 V neutral-ground voltage.

According to aforesaid analysis, the following suggestions are given:

1. If the neutral-ground voltage is below 10 V, you can think that it has no influences.

2. If the neutral-ground voltage is higher than 10 V,_check the ground-ground voltage between devices. If the voltage is below 2 V, you can think that the influence is small.

3. If the neutral-ground voltage is higher than 10 V, and the ground-ground voltage between devices is higher than 2 V, the data center needs to be reconstructed and the

ground voltage shall be reduced to below 2 V. Install the isolation transformer to the PDC and build another grounding system, to reduce the neutral-ground voltage to 0 V. The leakage inductance of the isolation transformer objectively plays a role of the filter and filters out high-frequency ripples of general voltage. This can help reduce the interference on data centers' devices. Installation of the isolation transformer is a method, while installation of the filter inductor is also an economical method.

6. Measures Adopted By Huawei UPS to Retrain Neutral-ground Voltage

The neutral-ground voltage below 10 V has no influence on data centers. However, many customers are skeptical about this. To reassure them, we adopt some measures to reduce the neutral-ground voltage.

Figure 10 Huawei UPS

a. The intensity of three-phase input currents of the UPS is the same. Even three-phase input voltages are imbalanced, through control by software, the intensity of three-phase power-frequency currents can be the same. After three phases are staggered for 120°, the intensity of power-frequency currents on N wire becomes 0. This helps reduce the intensity of power-frequency currents among i1 currents.

b. Stagger input three-phase carrier waves for 120°, to reduce high-frequency currents on the input N wire.

c. Increase the switching frequency and enhance internal filtering in the UPS. Reduce high-frequency ripples of input currents and output voltages, and reduce high-frequency currents on N wire.

d. Properly control the grounding capacitance and ground leakage currents in the UPS and reduce currents input by the UPS to the ground wire.

e. In building an data center, properly distribute three-phase load currents, and reduce power-frequency currents on the output N wire. Properly configure the diameter of N wire and PE wire and reduce impedance of N wire and PE wire. Ensure that N wire and PE wire are laid together to reduce the leakage inductance.

Descriptions

1. IBM's servers required a lower than 2 V neutral-ground voltage of data centers. However, IBM expressed that they raised such a requirement just to check whether N wire was properly connected.

2. Regulations for data center design of 2008 issue, *GB50174-2008 Regulations for Designing Data centers of Electronic Information Systems*, have the requirement for controlling the neutral-ground voltage below 2 V. However, multiple experts, after evaluating influences of the neutral-ground voltage on data centers' devices, thought that such a requirement was unscientific. This requirement will be deleted in the next issue of GB regulations for designing data centers.

Appendix 1: Huawei UPS's neutral-ground voltage test data

The following table shows the neutral-ground voltage test data of Huawei's transformer-less UPS. In all cases, using the mains power supply or batteries or with different loads, the neutral-ground power is always below 2 V.

200 kHz UPS			
The multimeter tests the neutral-ground voltage of UPS			
Load	Using Mains Power Supply (V)	Using Mains Power Supply and Batteries Alternatively (V)	Using Batteries (V)
No load	0.20	0.33	0.17
10%	0.48	0.49	0.17
30%	0.56	0.55	0.15
50%	0.63	0.63	0.15
70%	0.73	0.73	0.15
80%	0.84	0.84	0.16

90%	0.85	0.85	0.15
95%	0.87	0.88	0.15

Appendix 2: references

Analysis of Influences of Neutral-ground Voltage on Data Communication Devices; Zheng Xiao, Xie Qi, and Yu Pingfang

Scientifically Recognize the Neutral-ground Voltage Problem of Data centers' UPSs; Wang Wei

No Direct Influence of Zero Ground Potential of Data Center Power Systems on IT Equipment's Normal Operation; Zhang Guangming

Generation, Hazard, and Control of Neutral-ground Voltage on Power Supply Lines; Wang Lijian

Comprehensive Analysis on Neutral-ground Voltage of Data Centers; Li Quanwei

Two Methods to Effectively Eliminate Neutral-ground Voltage of Data centers; Wu Yunfeng; Zhang Jianhua

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