High-Efficient Power Supply Systems Utilizing 3-Phase 4-Wire Uninterruptible Power Systems

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ABSTRACT

In recent years, data centers have increasingly been using electricity, and their power supply systems need to improve efficiency. Fuji Electric has offered power supply systems using 400-V, 3-phase, 4-wire uninterruptible power systems, as well as 3-phase, 4-wire power supply systems using conventional 200-V, 3-phase, 3-wire power supply systems. Both types eliminate the need for a PDU transformer, achieving high efficiency. Using a current-limiting circuit-breaker enables short-circuit protective coordination. Furthermore, the I_{gr} method allows users to reliably monitor insulation and reduces the effect of harmonics on the *K*-factor and transformer equivalent capacitance more than standard power supplies.

1. Introduction

In recent years, data centers have increasingly been using electricity, which has created a demand for improved efficiency of uninterruptible power systems (UPSs). Fuji Electric has met this demand with the "UPS7000HX Series[(1)]" with 400-V output. The Series has achieved high efficiency by employing a non-insulated system and three-level conversion.

To further improve the efficiency of an entire data center, one method is to use a three-phase, four-wire UPS instead of a three-phase, three-wire type. It is capable of feeding directly to a server without a power distribution unit (PDU) transformer, saving space and cost while achieving high efficiency.

This paper presents a way to utilize three-phase, four-wire UPSs and the "UPS7000HX-T4," a three-phase, four-wire UPS offered by Fuji Electric. It also describes how to build a three-phase, four-wire system by using an insulated three-phase, three-wire UPS with an inverter transformer.

2. Comparison Between Three-Phase, Four-Wire and Three-Phase, Three-Wire Power Supply Systems

Three-phase, four-wire UPSs are widely in use outside Japan but not many examples of use are found in Japan. Three-phase, three-wire power supply systems, which are the mainstream in Japan, have benefits such as being able to handle server load harmonics and suppressing short-circuit currents due to the PDU transformer provided. This is assumed to be one reason why three-phase, four-wire power supply systems are not employed often.

Table 1 Comparison of three-phase, four-wire power supply system with three-phase, three-wire type

Items	Three-phase, four-wire system	Three-phase three-wire system
Efficiency	Good No PDU transformer	Fair PDU transformer provided
Space	Good No PDU transformer	Fair PDU transformer provided
Cost	Good No PDU transformer	Fair PDU transformer provided
Short-circuit current	Good Reduced with current-limiting circuit breaker	Good Reduced with PDU transformer
Insulation monitoring	Good Provided for input transformer	Fair Provided for input transformer and PDU transformer
Input transformer	Fair Measures for harmonic current required	Good Harmonic current dealt with by PDU transformer
Third and triplen harmonics	Fair Triplen harmonic superimposition	Good Dealt with by PDU transformer

Table 1 shows a comparison between three-phase, four-wire and three-phase, three-wire power supply systems; and Fig. 1, the main circuit wiring diagrams of the two power supply systems.

The three-phase, three-wire system is provided with a PDU transformer for converting the voltage into single-phase 230 V to be supplied to a server load. Meanwhile, the three-phase, four-wire system uses a four-wire UPS with the secondary voltage of the input transformer being 400 V. It can feed single-phase 230 V to a server load between the neutral and power supply phases, eliminating the need for a PDU trans-

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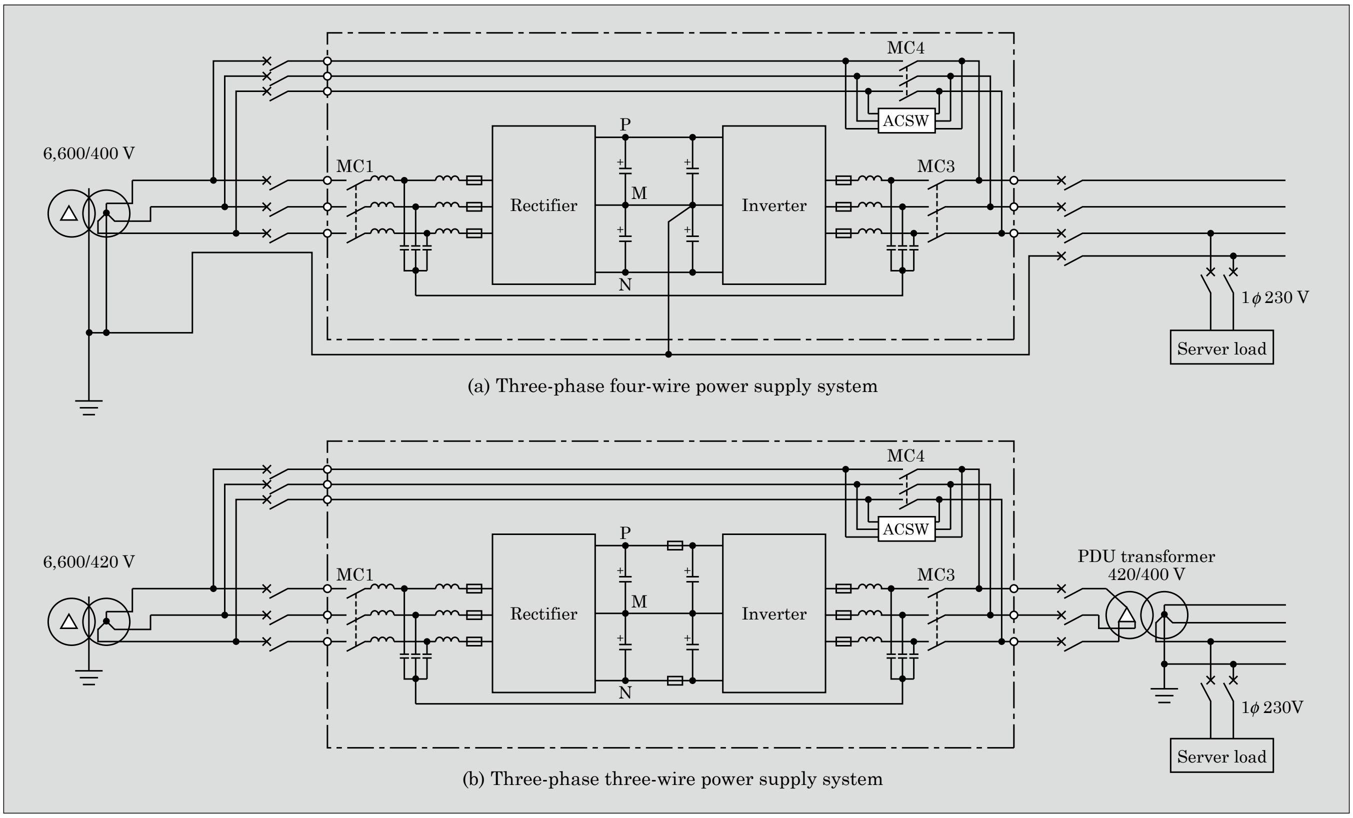

Fig.1 Main circuit wiring diagrams of three-phase, four-wire and three-phase, three-wire power supply systems

former. Therefore, in order to suppress an increase in short circuit current, a current limiting breaker is provided to perform protection coordination.

In three-phase, four-wire system, the third harmonic and triplen harmonic currents are superimposed on the neutral phase. In some cases, the current capacity of the neutral phase is made larger than the power phase. However, the current capacity of the neutral phase can be made equal to that of the power supply phase as described below, and this allows the system to reduce the introduction costs. In addition, ground fault can be monitored for a three-phase, four-wire UPS using an insulation monitoring device, improving system reliability.

3. Outline of Three-Phase, Four-Wire Power Supply Systems

3.1 Power supply system based on the “UPS7000HX-T4” (three-phase, four-wire)

The UPS7000HX-T4 (three-phase, four-wire type) is a large-capacity UPS with a 400-V output developed for data centers. Figure 1(a) shows the main circuit wiring diagram. Figure 2 shows the external appearance of the UPS7000HX-T4; and Table 2, the specifications. UPS7000HX-T4 provides a capacity of 500 kVA, alternating current (AC) input, bypass output and AC output at voltages of 380 V, 400 V and 415 V. The main circuit consists of an input filter circuit, rectifier, inverter and output filter circuit. The UPS has achieved high efficiency by employing a non-insulated system and three-level PWM control. While not shown in Fig. 1, a battery circuit is connected to the direct current (DC) intermediate part between the rectifier and inverter.

Fig.2 “UPS7000HX-T4”

The neutral phase of the star connection in the input transformer is grounded with Class B. The AC and direct feed inputs are drawn in with a three-phase, three-wire system and the neutral phase is connected to point M between the two capacitors in the DC circuit. No switch is provided between the neutral line of the transformer and the UPS so as to prevent the neutral phase from being cut off.

Table 2 “UPS7000HX-T4” specifications

Item		UPS7000HX-T4
AC input	Number of phases	Three-phase, four-wire
	Voltage	380/400/415 V
	Frequency	50/60 Hz
	Power factor	0.99 (delay) or more
Bypass input	Number of phases	Three-phase, four-wire
	Voltage	380/400/415 V
	Frequency	50/60 Hz
AC output	Rated capacity	500 kVA
	Number of phases	Three-phase, four-wire
	Voltage	380/400/415 V
	Voltage accuracy	< ±1%
	Frequency	50/60 Hz
	Frequency accuracy	±0.01 Hz (self-oscillating)
	Load power factor	Rating 0.9 (0.7 to 1.0)
	Transient voltage fluctuation	< ±5%
	Voltage waveform distortion factor	2% or less (linear load) 3% or less (nonlinear load)
	Overload capacity	125% × 10 min, 150% × 1 min
	Peak factor	<3
Battery	Rated voltage	480 to 528 V
	Floating charge voltage	540 to 594 V
Others	External dimensions	W1,630 × D1,000 × H1,950 (mm)
	Communication interface	SNMP

3.2 Three-phase, four-wire power supply system using the “UPS6000DX” (three-phase, three-wire)

The UPS6000DX (three-phase, three-wire) is an insulated UPS with 200-V input and output that has a transformer provided on the secondary side of the inverter. Figure 3 shows a three-phase, four-wire power supply system built by using the UPS6000DX Series. Insulated UPSs have features such as an ability to convert a rectangular wave voltage output of the inverter into a sine wave by using the function of the reactor of the inverter transformer and output voltage can be determined according to the specification of the load. They can also reduce short-circuit currents.

To build a three-phase, four-wire system with a three-phase, three-wire UPS, a delta-star connection is used for the inverter transformer to provide the neutral point. In the same way, the input transformer is delta-star-connected to provide the neutral point and the respective neutral points are connected together with the bus tie panel. The UPS provides feedback control for balancing the phase voltage between the neutral phase and the respective phases of the inverter transformer. Conventional UPS controls only the U- and W-phases but current one controls the three-phases to uniformly correct the respective phases, outputting a stable voltage output.

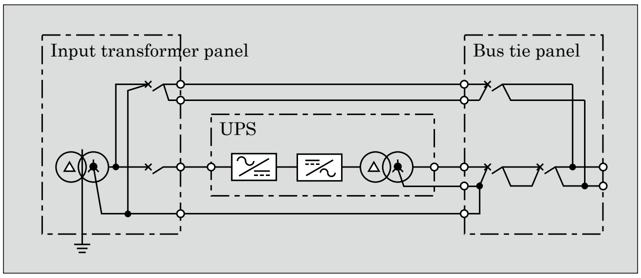

Fig.3 Three-phase, four-wire power supply system using “UPS6000DX” (three-phase, three-wire)

4. Short-Circuit Protective Coordination of UPS Systems

Redundancy power supply systems for data centers include standby redundant, parallel redundant and 2N systems. The respective systems use a single-unit UPS or multiple UPSs connected in parallel. A parallel system has a larger short-circuit withstand capability than a single-unit system, and short-circuit protective coordination is more difficult to achieve. For example, here we compare short-circuit protective coordination between a system with a single-unit capacity of 500 kVA and a parallel redundant system including eight 500-kVA units. Figure 4 shows their impedance maps. The trunk line is supplied through a 4P molded-case circuit-breaker (MCCB); and the line

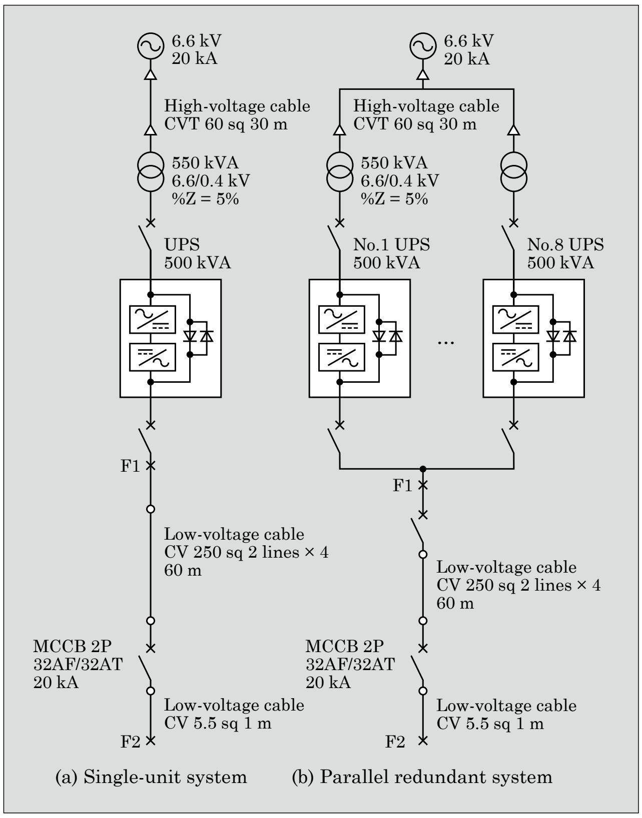

Fig.4 Impedance maps of single-unit and parallel redundant systems

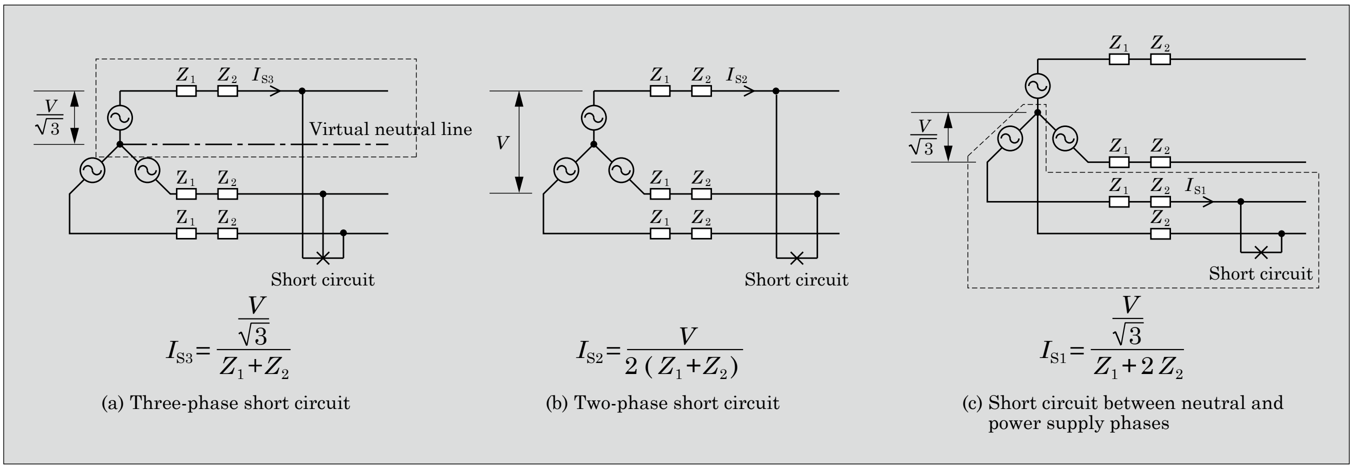

Fig.5 Short-circuit current calculation equation for three-phase short circuit, two-phase short circuit and short circuit between neutral and power supply phases

close to a server load, through a 2P MCCB. Figure 5 shows an equation for calculating short circuit current for a three-phase short circuit, two-phase short circuit and short circuit between the neutral and power supply phases. The ratio of each short-circuit current to that of a three-phase short circuit as the reference is as follows:

(a) The two-phase short-circuit current is $\sqrt{3}/2$ times the three-phase short-circuit current.

(b) The short-circuit current between the neutral and power supply phases is $(Z_1 + Z_2)/(Z_1 + 2Z_2)$ times the three-phase short-circuit current.

Z_1 is the total of impedances per phase on the power supply side including the transformer, and Z_2 is the cable impedance of the secondary side of the transformer and what follows.

The short-circuit current calculation conditions are as follows: a short-circuit current on the power supply side of 20 kA; input transformer 550 kVA with a percentage impedance of 5%; high-voltage cable CVT 60 sq of length 30 m; four low-voltage cable CV, 250 sq, 2 core of length 60 m; and low-voltage cable from the main line to the server load CV 5.5 sq of length 1 m. Table 3 shows the results of calculation.

The three-phase short-circuit current at point F1 directly under the UPS in the single-unit system is 15.1 kA (at 400 V) and the short-circuit current between the neutral and power supply phases at point F2 directly under the MCCB on the load side is 6.7 kA (at 230 V). MCCBs with 800 AT and 32 AT are mainly used for the UPS output and on the server load side. Short-circuit protective coordination is required between the MCCB on the load side and branch MCCB, and a current-limiting circuit breaker is used for the MCCB on the server load side. Figure 6 shows the cutoff characteristics of Fuji Electric's "BM Series" current-limiting circuit breaker with a 32 AT. The horizontal axis represents the short-circuit current obtained by calculation; and the vertical axis, the peak value of the current that flows at the time of cutoff resulting from operating the MCCB. The current-limiting circuit breaker of 32 AT can limit the short-circuit current of 6.7 kA to 2.0 kA (with a 2.8 kA peak). For the MCCB on the upper side, one with a characteristic of not starting instantaneous operation at 2.0 kA is selected for short-circuit protective coordination.

The three-phase short-circuit current at point F1 directly under the UPS in the eight-unit parallel redundant system can reaches very high current 91.5 kA, approximately six times that of the single-unit system.

Table 3 Short-circuit current value comparison between single-unit and 8-unit-in-parallel redundant systems

System	Point F1	Point F2 (Calculated value)	Point F2 (Cutoff current by current-limiting circuit breaker)
Single unit	15.1 kA	6.7 kA	2.0 kA
8 units in parallel	91.5 kA	10.6 kA	2.8 kA

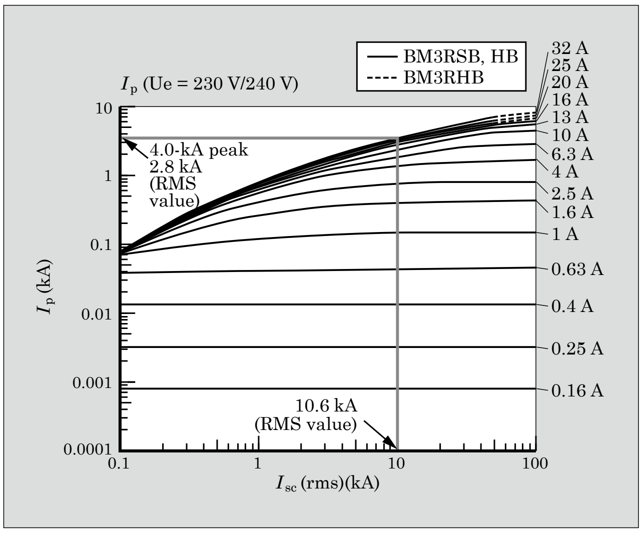

Fig.6 Cutoff characteristic of "BM Series" current-limiting circuit breakers

In the parallel bus part, an appropriate measure must be taken to prevent short-circuit accidents. Nevertheless, as shown in Fig. 6, the short-circuit current between the neutral and power supply phases at F2 directly under the MCCB on the load side is 10.6 kA but is limited by the current-limiting circuit breaker to 2.8 kA (with a 4.0 kA peak).

Short-circuit protective coordination can be easily achieved by using a current-limiting circuit breaker either in the single-unit or parallel system.

5. Ground Fault Protection of Low-Voltage Circuit

To protect the UPS and the server load from ground fault, the most reliable method is the I_{gr} method using an insulation monitoring device.

5.1 Ground-fault current of three-phase, four-wire UPS

With the input transformer provided on the primary side of the UPS, the contact-preventing plate and neutral phase of the secondary winding are grounded with Class B. The load voltage on the server side is 230 V and grounded with Class D. To the closed-loop circuit during a ground fault, the Class B grounding resistor of the neutral phase and Class D grounding resistor of the load on the server side are thus connected in series. Figure 7 shows how the ground-fault current flows and the calculation equation. In the main circuit of the non-insulated UPS, the insulated gate bipolar transistors (IGBTs) are provided with free wheeling diodes in anti-parallel configuration. Therefore, even if an insulation failure occurs on the load side, a closed-loop circuit is formed through the free wheeling diode when one IGBT is turned on, allowing the ground-fault current to be detected.

5.2 Insulation monitoring of UPS system

Insulation monitoring devices of UPS systems may be one of three types depending on the method used: I_o, I_{or} or I_{gr} method.

(a) The I_o method uses a zero-phase-sequence current transformer (ZCT) to detect a leak current.

(b) The I_{or} method uses the system voltage as the reference and detects a current by insulation resistance. The I_{or} and the current I_{oc}, which flows through ground capacitance, are separated and extracted by computing.

(c) The I_{gr} method superimposes an electric current from a power supply with different frequency from the commercial power supply on the current between each power supply and the ground and monitors insulation by measuring active current. A superimposed voltage of 0.5 V and frequency of 20 Hz, for example, are used for detecting active current of the same phase as that of this power supply.

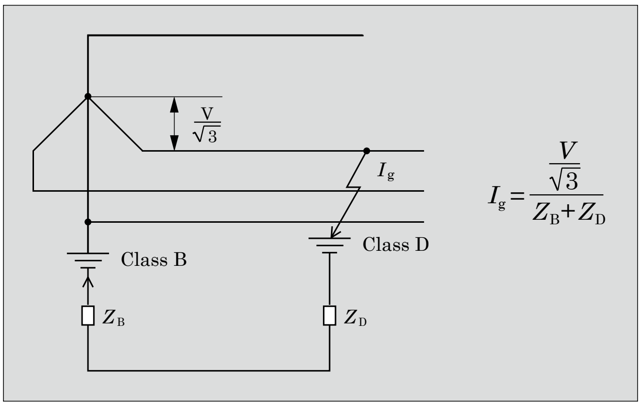

Fig.7 Ground-fault current equivalent circuit and calculation equation

Of these, the I_{gr} method has features such as no effect of capacitance, the ability to detect insulation deterioration of the ground and neutral phases, detection of three-wire balance insulation deterioration, and insusceptibility to an imbalance of the ground capacitance, and it provides a reliable insulation monitoring.

With the I_{gr} method, an I_{gr} power supply can be inserted into the neutral phase of the secondary side of the star connection in the input transformer of a non-insulated UPS to monitor the insulation of the power system including the UPS main body. With some insulation devices, however, the ground capacitance is limited, and the ground capacitance of the grounding capacitor in the UPS, cable and the load side must be calculated to consider whether or not to adopt this method.

6. Dealing with Harmonic Currents

Harmonic currents can affect the UPS input transformer capacity and current capacity of the neutral phase. The input transformer, to which a harmonic load is directly connected when the UPS is switched to the bypass, must be selected in view of the capacity required when a harmonic current flows. Therefore, the transformer equivalent capacitance based on the limits for harmonic current emissions of JIS C 61000-3-2 and the *K*-factor value specified in the UL standard must be calculated. The third harmonic current and any integer multiple of the three have the same phase because there is no difference in the phase angle, and a current flows in the neutral phase is three times as large as that in each power supply phase. When the neutral phase current can exceed the rated current of the MCCB, the current capacity of only the neutral phase must be made large. Accordingly, we see if the current capacity can be made the same level as the power supply phase.

JIS C 61000-3-2 specifies the limits for harmonic current emissions for devices with an input current per phase of up to 20 A. For the harmonic current limits, devices can be grouped into four classes: A, B, C and D. The limits for the largest allowable harmonic current of Class A, into which server power supplies are classified, are specified to be 2.3 A for the third harmonics and 1.14 A for the fifth harmonics.

Generally, the winding loss of a transformer consists of a resistance loss (I^2R) and stray load loss. With harmonics, the stray load losses (including eddy current loss and harmonic loss) in the winding loss significantly increase, and this can cause abnormal overheat of the windings. Accordingly, the transformer capacity is selected by defining the equivalent base current so that the winding loss is the same as the load loss.

$$I_e = K_P \times I_1 \quad (1)$$

I_e : Equivalent base current
K_p: Equivalent capacitance coefficient
I_1 : Fundamental current

There is a factor called K-factor, which indicates the degree of inclusion of the harmonic component and is shown by the equation below, and a larger value of this factor indicates more harmonic component included.

$$K = \Sigma F_n^2 \times I_n^2 \quad (2)$$

F_n: Harmonic order
I_n : Ratio of harmonic current to fundamental current

By using this K-factor, an acceptable harmonic load can be determined that does not cause overheating of the transformer. The UL1561 standard specifies stepwise K-factors such as 4, 9, 13, 20, ... and provides that the temperature rise of windings shall not exceed the upper limit of the standard during the operation under the corresponding conditions. Generally, 13 is applied. PDU panels employed by data center operators and computer centers require K-factor transformers.

Table 4 shows the effect of using standard products specified with harmonic current reduction. The effect is shown by the results of calculation for a common power supply with the load harmonic current grouped into Class A of JIS C 61000-3-2 (fundamental current 20 A) and Fuji Electric's server power supply. As compared with the common power supply, Fuji Electric's power supply offers the K-factor of 1.20, transformer equivalent capacitance of 1.01 and the content of triplen harmonics of 42.5%, showing less effect of harmonics, and the transformer capacity and the current capacity of the neutral phase can be made the same level as the power supply phase.

Table 4 Effect of use of standard products specified with harmonic current reduction

Condition	K-factor	Transformer equivalent capacitance I_e	Content of triplen harmonics (%)
JIS C 61000-3-2 Class A	1.72	1.03	58.7
Fuji Electric's power supply	1.20	1.01	42.5

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7. Postscript

This paper has described high-efficiency power supply systems utilizing three-phase, four-wire UPSs. We have shown that the three-phase, four-wire type can be used without any problem by considering the required technical factors in building a three-phase, four-wire power supply system. We hope that, as a result, more three-phase, four-wire UPSs will be employed. In the future, we intend to continue to work on energy savings of power supply systems and meet customers' expectations.

References

(1) Yamagata, Y. et al. "UPS 7000HX Series" of High-Efficiency, Large-Capacity UPS Products Using AT-NPC 3-Level for Data Centers. FUJI ELECTRIC REVIEW. 2012, vol.58, no.4, p.207-211.

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