Power System Construction Technology with Improved Redundancy and Maintainability

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ABSTRACT

The capacity of uninterruptible power systems (UPSs) has been expanding to meet the needs of larger data centers. Power systems with UPSs face various challenges, such as ensuring redundancy during maintenance, preventing erroneous operation, and suppressing voltage fluctuations during power supply switching and energizing of large-capacity transformers. The measures to build a power supply system with enhanced redundancy and maintainability include an N+2 system to ensure redundancy and sequence circuits using a rotation control key switch to prevent erroneous operation. In addition, inrush exciting current, a cause of voltage fluctuations, can be suppressed through the sequential closing of circuit breakers during a power supply switching and the replacement of two parallel high voltage transformers with a single high capacity transformer.

1. Introduction

In recent years, there has been an increase in the construction of data centers (DCs) as companies move information systems to the cloud and expand their use of e-commerce. In addition, DCs have been increasingly consuming more power due to their use of large-capacity and high-density servers and storage devices. As a result, there is a need to increase the efficiency and capacity of the uninterruptible power systems (UPSs) that feed power to their loads.

In order to achieve higher efficiencies, Fuji Electric has been developing three-level control, three-phase, four-wire UPSs[1], UPSs that combine the features of normal inverter feeding and continuous commercial power feeding[2], and quantity control functions for parallel redundant configurations. We also offer UPSs that use lithium-ion batteries[3]. Furthermore, we are developing a high-capacity UPS system for large-scale DCs.

However, there are also some challenges that need to be addressed when using high-capacity equipment. An increase in UPS capacity lead to the increased capacity of high-voltage transformers. This, in turn, increases the inrush exciting current and results in a larger voltage drop when the power supply is activated. This degradation in power quality can cause load stoppages and unnecessary power supply switching during power restoration and maintenance. Meanwhile, N*1+1 (one stand-by unit is installed as a backup) redundant system loses its redundancy during maintenance and failures. This has created the need to ensure redundancy at such times. An N+2 redundancy system keeps its redundancy during maintenance and failures, but the optimal equipment configuration for this type of system needs to be carefully considered.

In this paper, we describe a technology for constructing power supply systems with enhanced redundancy and maintainability.

*1 N: UPS system configurations generally use the term N. N refers to the number of UPSs equal to the load capacity.

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2. Overview of Large-Scale Power Supply System

Figure 1 shows an example of a large-scale DC power supply system configuration. The power supply system consists of extra-high-voltage substation equipment, secondary substation, UPS system equipment, and emergency power generation equipment.

The extra-high-voltage substation equipment generally uses a primary and stand-by configuration as a means of receiving power. In such a case, redundancy is ensured for the extra-high-voltage power-receiving circuit breaker, extra-high-voltage transformer, and extra-high-voltage secondary circuit breaker. The maximum contracted power of a receiving voltage of 66 kV is 50 MW and consists of two or four 25- to 30-MVA extra-high-voltage transformers. Therefore, secondary substations are installed at 8 to 10 locations. Each of these secondary substations has a capacity of 3 MVA for receiving power from a single extra-high-voltage transformer. The UPS system equipment is redundant, consisting of multiple high-capacity UPS systems, as well as stand-by units. The emergency power generation system is also redundant, consisting of primary and stand-by units.

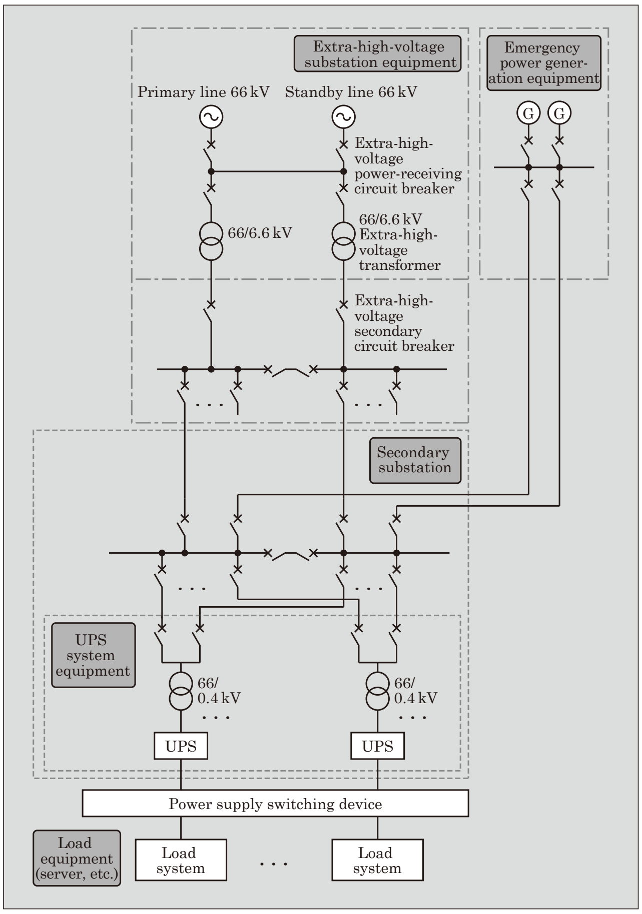


Fig.1 Example of power system configuration for a large-scale data center

3. Challenges Facing Conventional Power Supply Systems

3.1 Ensuring redundancy during maintenance

The N+1 configuration has been often used for redundant UPS systems. However, keeping its redundancy during maintenance and failures is a challenge because the stand-by unit is not available.

3.2 Preventing misoperation during maintenance

UPS maintenance requires power supply switching. This involves releasing the interlock that prevents the UPS from using both inverter and commercial power feeding. However, preventing misoperation is a challenge. If the circuit breaker used for supplying power is accidentally opened after the interlock is released, power supply can be interrupted.

3.3 Suppressing voltage fluctuations caused by power supply switching during maintenance

For the following reasons, it is a challenge suppressing voltage fluctuations caused by power supply switching during maintenance.

(a) In UPS systems, common backup or 2N (where N stand-by units are installed as backups) is a highly reliable redundant configuration. However, if each of the UPSs receives power from a different extra-high-voltage transformer, phase displacement will occur in the output voltage of each UPS due to differences in the load factor of the extra-high-voltage transformers. Operating the load switching device in such an asynchronous state takes 0.1 to 0.2 s to switch the UPS, during which time the power supply to the load is stopped.

(b) When receiving power in a normal and stand-by configuration, the extra-high-voltage power-receiving circuit breaker, extra-high-voltage transformer, and extra-high-voltage secondary circuit breaker of the extra-high-voltage substation equipment are redundant, but the secondary substation is cut off due to power supply switching when those devices undergo maintenance.

(c) Because of the use of a large-capacity UPS, the capacity of a high-voltage transformer increases, the magnetizing inrush current of the transformer also becomes large, and the voltage fluctuation when the power is turned on becomes larger than small capacity system.

4. Constructing Power Supply Systems with Enhanced Redundancy and Maintainability

4.1 Ensuring redundancy during maintenance

(1) Comparison of N+2 redundant UPS systems

To ensure redundancy during times of maintenance, there are N+2 (two stand-by units installed as backups) configurations available for UPS system facilities. Table 1 shows a comparison of parallel redundancy, stand-by redundancy, and common backup (catcher method) in an N+2 redundant UPS system.

(a) Parallel redundancy

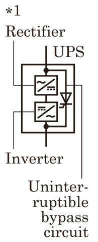
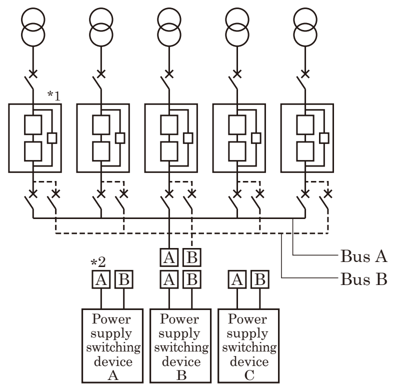
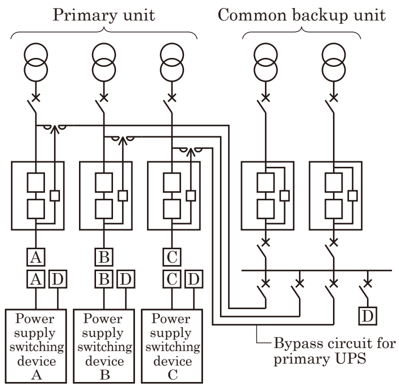
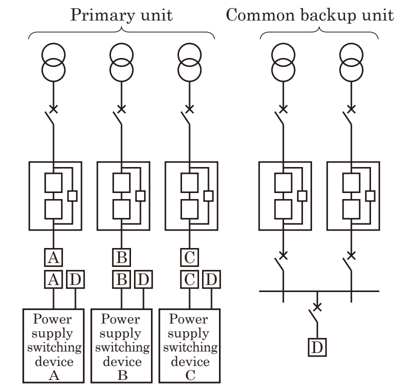
If one UPS output short-circuits, a short-circuit current flows to all remaining UPSs. As a result, it becomes necessary to take short-circuit protective coordination and bus circuit isolation measures.

If one UPS fails and stops, the healthy UPSs continue to supply power to the load. However, if multiple UPSs fail, the healthy UPSs also become overloaded and stop due to load concentration. In such a case, all UPSs must switch to the uninterruptible bypass circuit to continue supplying power to the load.

(b) Stand-by redundancy

If the UPS output of a primary unit is shorted, the corresponding UPS switches to the uninterruptible bypass circuit. At that time, the UPS of the common backup unit continues to supply power. However, a short-circuit current also flows to the UPS of the common backup unit, and it is also switched to the uninterruptible bypass circuit. Therefore, short-circuit protective coordination is necessary to determine the operational order of cir-

Table 1 Comparison of parallel redundancy, stand-by redundancy, and common backup (catcher method) in an N+2 redundant UPS system

	Parallel redundancy	Stand-by redundancy	Common backup (catcher method)
Configu-ration diagram 			
System opera-tion	○ All UPSs share the load and operate in parallel. ○ The load is selected and receives power from bus A or B.	○ Two common backup units in parallel ○ The load is selected and receives power from a primary unit and a common backup unit.	○ Two common backup units in parallel ○ The load is selected and receives power from a primary unit and a common backup unit.
Reliabil-ity	○ Distributed uninterruptible bypass circuit ensures the supply of power. ○ Short-circuit protective coordination requires attention because short-circuit current flows from all UPSs when a short circuit occurs.	○ Requires switching to uninterruptible bypass circuit at times of failure. ○ Control is complicated for the power supply switching device when multiple units fail. ○ Short-circuit protective coordination requires attention because short-circuit current flows through both the primary UPS and backup UPS when a short circuit occurs.	○ Requires switching to uninterruptible bypass circuit at times of failure. ○ Does not require a power supply switching device for the bypass circuit. ○ Short-circuit current flows only to the relevant UPS when a short circuit occurs, and therefore the impact on other UPSs is small.
UPS out-put	Synchronous	Synchronous	Non-synchronous (Adding external synchronous control allows for synchronization)
Main-tainabil-ity	Maintain one unit at a time while continuing to supply power with the UPS that ensures redundancy.	Maintain one unit at a time while continuing to supply power with the UPS.	Maintain one unit at a time while continuing to supply power with the UPS.

*2 A B C D : Connect with the same symbols

cuit breakers.

If the UPS of a primary unit fails, the common backup unit is connected to the uninterruptible bypass circuit of the failed UPS in order to continue supplying power. However, if more than one unit fails, control becomes complicated because the power supply switching device installed in the uninterruptible bypass circuit of the UPS of the primary unit must switch the power supply appropriately.

(c) Common backup (catcher method)

Even if the UPS output of a primary unit is shorted, the short-circuit current does not flow to or affect the other UPSs. As a result, load operation can be continued by switching to the power feed from the UPS of the common backup unit. If the UPS of the primary unit fails, power will continue to be supplied since it switches to the uninterruptible bypass circuit.

This is a highly reliable configuration, and it also features a significantly simpler circuit configuration compared with the other methods.(4)

In light of the above, it can be said that common backup (catcher method) is superior in terms of overall reliability and economic efficiency.

(2) Suppressing voltage fluctuation during UPS switching using an external synchronization method

During maintenance of the primary unit of the common backup (catcher method), the power supply switching device is used to switch from the primary unit to the common backup unit. However, the switching is accompanied by voltage fluctuations when it is in an asynchronous state where the voltage phase of the primary unit and common backup unit are different from each other.

Therefore, it uses external synchronization with a loop connection to keep the voltage output of each UPS in a synchronized state at all times. This enables a fast switching time of 5 ms with no impact on the load.

Figure 2 shows the external synchronization method using a loop connection. A communication board is installed in each UPS, and loop connection is made with a communication cable. Even if the communication cable is disconnected or the communication board is damaged, it maintains connection between each UPS, enabling synchronous control to continue. Synchronous control is basically implemented as follows:

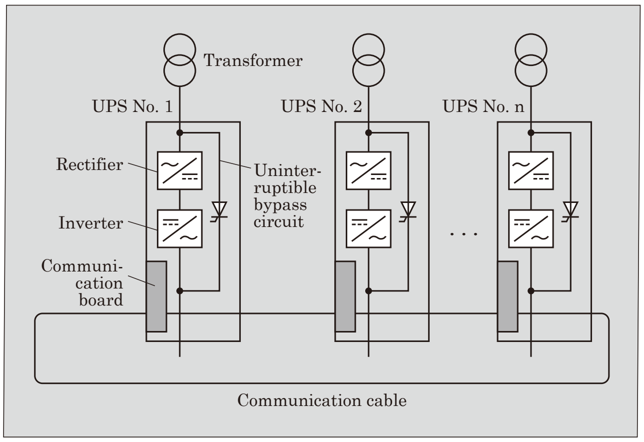


Fig.2 Configuration of external synchronization method using loop connection

(a) Synchronize to each UPS bypass power supply when each AC input power supply is synchronized.
(b) Select a normal UPS output and operate it according to its phase when the phase of the AC input power supply fluctuates.
(c) Select a normal UPS output and operate it according to its phase when the AC input power supply stops.

4.2 Preventing misoperation during maintenance

It uses a circuit with a rotation control key switch to prevent misoperations. The rotation control key switch has a solenoid and key switch auxiliary contact. The key switch can be rotated by exciting the solenoid. The rotation of the key switch is controlled by a sequence circuit, and the key cannot be removed when it is inoperable.

As an example, Fig. 3 shows the maintenance procedure for a UPS system that uses a rotation control key switch to prevent misoperations.

(1) During normal operation

The UPS output circuit breaker cannot be operated when it is ON, and the maintenance bypass circuit breaker cannot be operated when it is OFF. The key inserted into the rotation control key switch of the maintenance bypass circuit breaker is fixed in the operation-prohibited position and cannot be removed.

(2) Switching from inverter power feeding to bypass power feeding

When switched to bypass power feeding, the rotation control key switch of the maintenance bypass circuit breaker becomes rotatable. When it is placed in the circuit breaker lock-released (keyed) position, the circuit breaker operation lamp lights up and the maintenance bypass circuit breaker becomes operable.

(3) Energizing the maintenance bypass circuit

Closing the maintenance bypass circuit breaker will turn on the circuit breaker operation lamp on the UPS output circuit breaker and will allow the UPS output circuit breaker to be operable. The key on the maintenance bypass circuit breaker side is switched to the UPS circuit breaker side.

(4) Performing UPS system maintenance

When the UPS output circuit breaker is opened, the circuit breaker operation lamp on the maintenance bypass circuit breaker side turns off and the maintenance bypass circuit breaker becomes inoperable. In order to prevent the UPS from being energized during maintenance, the UPS output circuit breaker becomes inoperable when the rotation control key switch is placed in the operation lock (keyed) position. In this position, maintenance of the UPS system can be performed.

4.3 Suppressing voltage fluctuations caused by power supply switching during maintenance

(1) Uninterruptible power supply switching

Power supply switching is necessary when performing maintenance for extra-high-voltage substation equipment, secondary substations, and UPS system equipment. Figure 4 shows the uninterruptible power supply switching during maintenance.

(a) During maintenance of extra-high-voltage power-receiving circuit breakers

Uninterruptible power supply switching is possible by using loop switching, a method in which the power-receiving circuit breakers of the primary and stand-by lines are closed and put into a wrapped

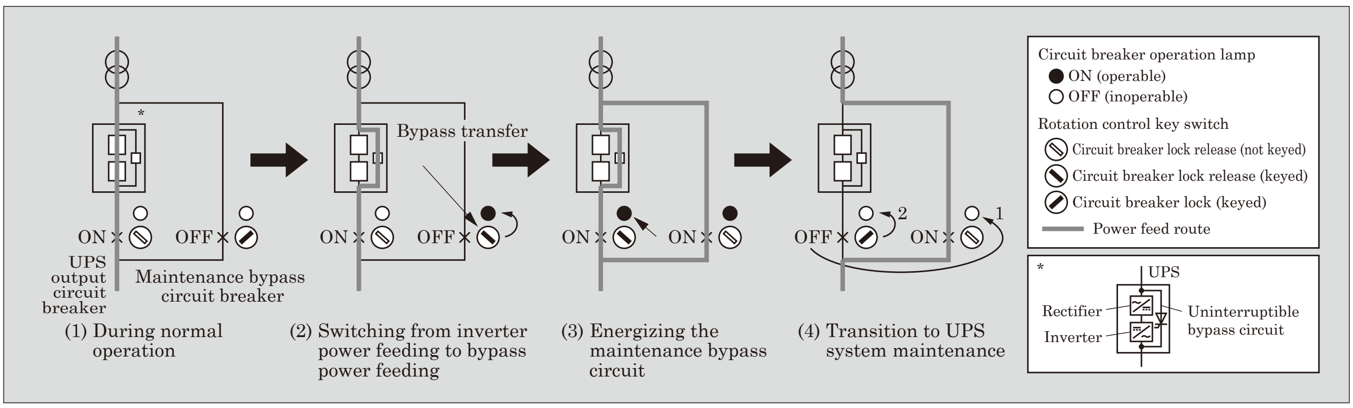


Fig.3 UPS system maintenance procedures

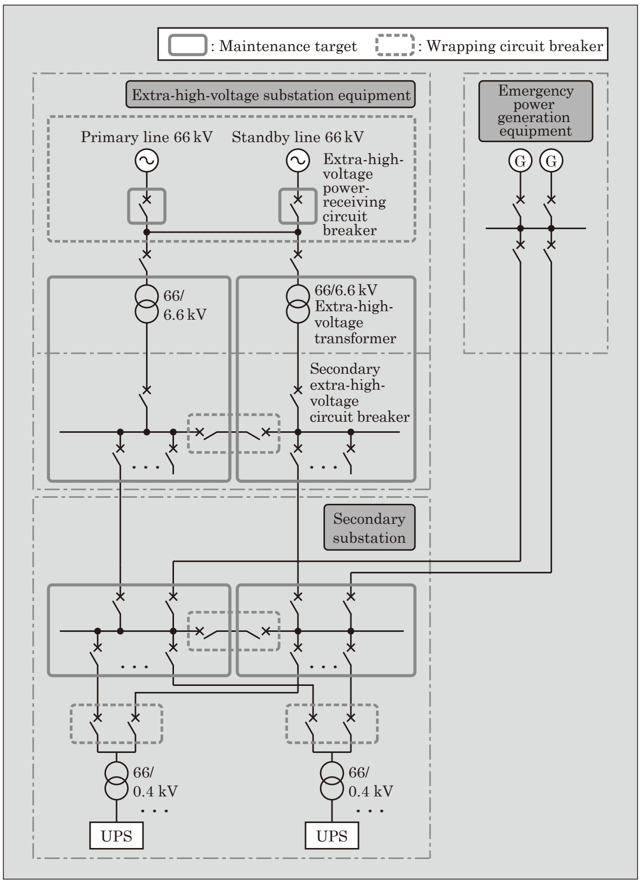


Fig.4 Uninterruptible power supply switching during maintenance

state*2. However, during loop switching, cross current flows between the primary and stand-by lines due to the difference in impedance between the two systems and the load factor on the system side. Therefore, it is necessary to fully consult with transmission system operators about the setting values of short-circuit and ground-fault relays, relay locks during switching, and other relevant matters.

(b) During maintenance of extra-high-voltage transformers

After the circuit breaker linking with the high-voltage bus on the secondary side of the extra-high-voltage transformer is activated (during wrapping), the circuit breaker on the secondary side of the transformer is opened. As a countermeasure against short circuits during wrapping, it is necessary to select equipment with twice the breaking capacity for the circuit breakers beyond the secondary bus of the extra-high-voltage transformer, because twice the short-circuit current will flow through them.

(c) During maintenance of secondary high-voltage circuits of extra-high-voltage transformers

After wrapping the circuit breaker that links with the high-voltage bus on the secondary side of the extra-high-voltage transformer, it is necessary to wrap the circuit breaker that links with the high-voltage bus on the secondary substation side. After doing this, the secondary high-voltage circuit of the extra-high-voltage transformer to undergo maintenance must be stopped. However, there will be transmission on two lines for the secondary side of the extra-high-voltage transformer and the high-voltage bus of the secondary substation during wrapping, and the three-phase current may become unbalanced due to differences in the impedance of each cable. This can cause the detection of ground faults. Therefore, the ground-fault relay should be locked during wrapping.

(d) During maintenance of the high-voltage circuit of the secondary substation

The circuit breakers of the secondary side of the extra-high-voltage transformer, the secondary substation, and the primary side of the UPS can be maintained by wrapping them.

(2) Suppressing voltage fluctuations during high-voltage transformer activation

(a) Voltage drop due to transformer inrush exciting current

The inrush exciting current of Fuji Electric's high-voltage transformers is approximately eight times the rated current, and its time constant increases in proportion to the capacity. Table 2 shows the calculation results of the momentary voltage drop due to the inrush exciting current*3 of the high-voltage transformer. Calculation conditions include a short-circuit withstand capacity of 2,500 MVA on the system side and an instantaneous transient reactance of 28%. The maximum voltage drop due to the activation of a high-voltage transformer powered by utility power is 8%. When power is fed by emergency power generation equipment, the voltage drop can exceed 20% due to the large transient reactance of the generator.

(b) Sequential activation of high-voltage circuit breakers

It is necessary to avoid simultaneous activation of high-voltage transformers because voltage drops

Table 2 Calculation results of the momentary voltage drop due to the inrush exciting current of the high-voltage transformer (Capacity of the transformer to be activated is 2,000 kVA)

Power supply system	Capacity (MVA) × No. of units	Voltage drop rate (%)
Utility power	25 × 1	8.1
Emergency power generation equipment	6 × 2	20.3

*2 Wrapped state: The state of two lines being connected to a single bus.

*3 Transformer inrush exciting current: The inrush current that is generated when a voltage is applied while the transformer is not energized.

can cause load stoppages and unnecessary power supply switching. Therefore, the high-voltage circuit breakers (HVCBs) are sequentially activated at intervals of approximately twice the time constant*4.

An extra-high-voltage substation equipment of 66 kV is typically accompanied by secondary substations at 8 to 10 locations. For example, if there are 10 secondary substation HVCBs for each extra-high-voltage transformer, then 80- to 100-HVCBs will need to be activated in sequence.

There are several patterns for activating secondary substation HVCBs. These include when both systems are being restored to power, when one system is being restored to power, when power is restored during maintenance, and when power is fed by generators.

There are many HVCBs and various activation patterns available, it is thus important to configure the activation interval of the HVCBs so that they do not activate at the same time. Figure 5 shows an example of a flowchart during utility power restoration.

A group consists of two secondary substations, and the HVCBs within the group are activated at an interval of 1 second. The HVCB activation interval after restoring each secondary substation is common to all units. The activation command received from the secondary side of the extra-high-voltage transformer is acquired at 0.3-second intervals for each group to prevent simultaneous activation of the HVCBs.

(c) Example of technology for suppressing inrush exciting current in large-capacity high-voltage transformers

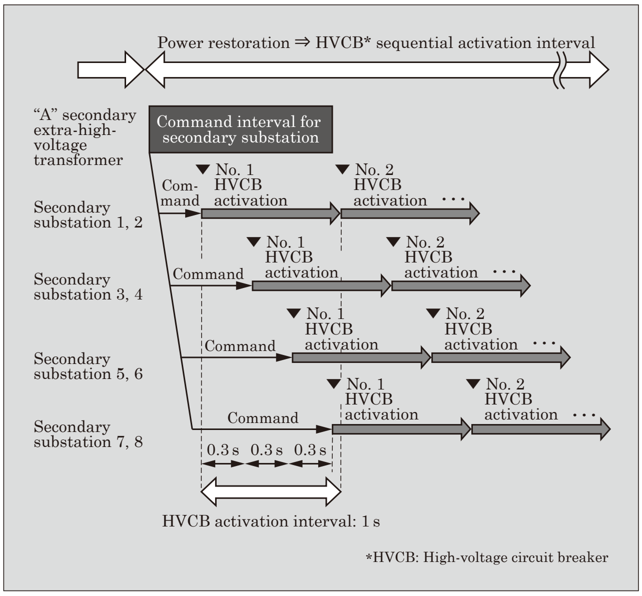


Fig.5 Example of a flowchart during utility power restoration

*4 Time constant: The time required for the inrush current to decrease to 1/e.

Table 3 Comparison of inrush exciting current of two 1,500-kVA units and one 2,660-kVA unit

Item	1,500 kVA × 2 units (Parallel redundancy)	2,660 kVA × 1 unit (Self-cooled 2,000 kVA)
Cooling system	Natural cooling	Fan cooling
%Z (%)/ rated capacity	5.4	8.3
Inrush exciting current (A) (crest factor)	1,520 × 2 units = 3,040	1,700
Rated efficiency (%)	99.3	98.8
75% capacity efficiency (%)	99.4	99.0

As UPS system capacity increases, voltage drop due to inrush exciting current in large-capacity high-voltage transformers becomes significant. For example, a 2,400-kVA UPS system uses a 2,660-kVA high-voltage transformer to have a voltage margin for UPS loss and battery charging. The standard high-voltage transformers, which is up to 2,000 kVA, is typically combined with two 1,500-kVA transformers in parallel. However, this creates the risk of overlapping inrush exciting current for the two units. Meanwhile, developing a new 2,660-kVA high-voltage transformer would cause other problems, such as increase in size and mass. That is because it becomes necessary to take measures to suppress the inrush exciting current, such as lowering the magnetic flux density of the iron core and increasing the number of turns to increase inductance. As a solution, we have delivered the capacity of 2,660 kVA by utilizing a 2,000-kVA self-cooled transformer and cooling it with a fun to suppress the size, mass, and inrush exciting current.

Table 3 compares the inrush exciting current of two 1,500-kVA units and one 2,660-kVA unit. Using fewer number of units with one 2,660-kVA unit achieves compactness and the significant reduction of inrush exciting current. When the single 2,660-kVA UPS system is operated in an N+1 redundant system, a load factor (75% capacity efficiency at N = 3) of 99.0% can be ensured during normal operations.

5. Postscript

In this paper, we described a technology for constructing power supply systems with enhanced redundancy and maintainability.

The N+2 redundant UPS system showed excellent reliability and economic efficiency through the use of common backup (catcher method). We also showed that voltage fluctuations can be suppressed during maintenance by using external synchronous control of UPSs, avoiding power failure switching due to power supply wrapping, and utilizing forced cooling of large-capacity transformers.

Looking ahead, Fuji Electric will continue to provide highly reliable power supply systems.

References

(1) Yasumoto, K. et al. High-Efficient Power Supply Systems Utilizing 3-Phase 4-Wire Uninterruptible Power Systems. FUJI ELECTRIC REVIEW. 2019, vol.65, no.1, p.58-63.

(2) Yasumoto, K. et al. "UPS7000HX-T4" High-Efficiency UPS with Continuous Commercial Power Feeding and Quantity Control Function. FUJI ELECTRIC REVIEW. 2019, vol.65, no.3, p.151-155.

(3) Yasumoto, K. et al. "UPS7000HX Series" and "UPS6000DX Series," Using Lithium Ion Batteries. FUJI ELECTRIC REVIEW. 2018, vol.64, no.4, p.221-226.

(4) Yasumoto, K. et al. "Common Backup Systems for Data Centers with Large-Capacity UPS. FUJI ELECTRIC REVIEW. 2020, vol.66, no.1, p.72-78.