Industrial-Use Power Supplies Contributing to Stable Operation of Material Manufacturing Equipment

WATABE, Kohei*　OKAZAKI, Yohei*　ASADA, Masato*

ABSTRACT

Various types of industrial power supplies are used in material manufacturing equipment depending on the application. Among them, transformer rectifiers for aluminum smelting have large capacities more than several hundred MVA per unit, posing specific issues. To address the issues, Fuji Electric has adopted an optimum design based on various simulations and harmonic system analyses. As a result, we have downsized the transformer rectifier and improved its reliability by increasing analysis accuracy and optimized materials, confirmed the safety in an accident by simulating the short-circuit fault in the rectifier, and prevented power quality deterioration in the entire power supply system by analyzing the harmonics generated from the transformer rectifier.

1. Introduction

Depending on the application, various types of industrial-use power supplies such as transformer rectifiers (DC power supplies), AC power regulators, special waveform power supplies, high-frequency power supplies, flicker compensators and static var compensators are used in material manufacturing equipment for nonferrous metals, steel, chemicals, semiconductors, and green hydrogen.

Industrial-use transformer rectifiers are used for the power supplies of the equipment for material manufacturing processes, such as electrolysis, melting, smelting and heating. The material manufacturing industry is the foundation of all industries. Investment in equipment continues to expand worldwide, and the market for industrial-use transformer rectifiers is also expanding.

Transformer rectifiers for aluminum smelting are one such equipment with large capacities exceeding several hundred MVA, and therefore, they are accompanied by a number of challenges to be addressed, including the implementation of countermeasures against harmonics, size reduction, and ensuring safety in the event of an accident. Fuji Electric is making efforts to overcome these challenges by optimizing the design of equipment using simulation analysis technology, including verification not only of the transformer rectifier units as standalone devices, but also of power supply systems as a whole.

This paper describes industrial-use power supplies that contribute to the stable operation of material manufacturing equipment.

* Power Electronics Energy Business Group, Fuji Electric Co., Ltd.

2. Overview of Transformer Rectifiers

Transformer rectifiers convert high-voltage and extra-high-voltage AC power to low-voltage, high-current DC power. It is used for smelting processes for various metals and electrolytic processes at chemical plants.

For 60 years, Fuji Electric has provided industrial-use transformer rectifiers of a wide range of capacities to customers around the globe. The development, installation and construction of transformer rectifiers require high-current application technologies (local heating suppression and magnetic flux control) as well as the optimization and high-reliability design of systems with consideration for impact on the grid, and Fuji Electric has the advanced technological capabilities to meet these requirements.

Figure 1 shows a bird's-eye view of a transformer rectifier for aluminum smelting equipment.

As aluminum electrolysis is a molten salt electrolysis procedure, the disconnections of a DC power

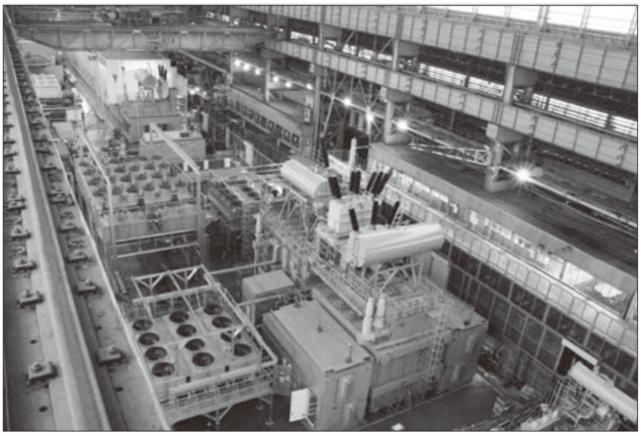


Fig.1 Transformer rectifier for aluminum smelting equipment

source causes the solidification of molten aluminum and significantly damages the electrolytic equipment; therefore, DC current losses of one hour or longer must be avoided. For this reason, rectifiers generally employ diodes because of relatively high reliability. In some cases, multiple rectifiers are installed for redundancy to prepare for failures.

Figure 2 shows a skeleton diagram of typical aluminum smelting equipment. The voltage regulating transformer steps down extra-high-voltage AC power and the transformers for the rectifiers and the rectifiers feed DC power to electrolytic equipment. Harmonic filters are installed to improve power factor and reduce harmonics flowing to the power supply, increasing power quality.

Anode effect (AE) that occurs during molten salt electrolysis temporarily increase the load resistance during operation. To compensate for this and enable operation at a constant current, an on-load tap changer for coarse control of DC voltage (built into the voltage regulating transformer) and a voltage control reactor (VCR) for fine control are installed in the transformer rectifier.

As indicated in Table 1, the electrical specifications required for the electrolytic equipment are increasing year by year, and in turn, transformer rectifier capacities have also been continuously increasing. Increasing capacities have brought about the need to address challenges in the following ways:

○ Implementing countermeasures against harmonics to prevent power supply quality loss
○ Reducing the size (small footprint)
○ Improving design reliability for higher voltages and higher currents
○ Ensuring safety

Following chapter describes Fuji Electric's efforts to solve these issues for transformers, rectifiers, and power supply systems as a whole.

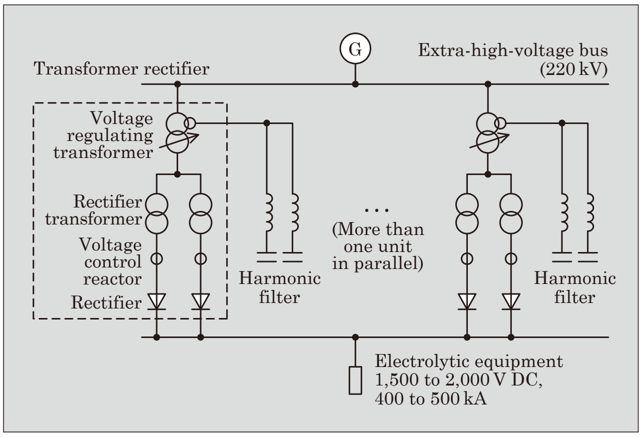


Fig.2 Skeleton diagram of general aluminum smelting equipment

Table 1 Required electric specifications of aluminum smelting equipment

	1960's	1990's	From 2010 to now
DC voltage	500 V	1,250 to 1,600 V	1,800 to 2,000 V
DC current	50 to 120 kA	310 to 370 kA	400 to 500 kA
DC power	25 to 60 MW	350 to 500 MW	700 to 900 MW

3. Efforts for Transformers

3.1 Suppressing impedance fluctuation through changes in winding arrangement

Voltage regulating transformers of transformer rectifiers for aluminum refining equipment are required to continuously control DC voltage from 0 V to the rated voltage (2,000 V maximum). They thus often use a 107-tap multi-varying on-load tap changer (OLTC).

When the tap position changes, the impedance fluctuates, causing power supply quality loss. Impedance fluctuations are particularly large where the coarse tap position changes. For this reason, the latest equipment uses a structure in which the primary and secondary winding are reversed compared to the conventional winding arrangement. Figure 3 is an example of the change in impedance between the primary winding and secondary winding. It shows that the impedance fluctuation is smaller after the change in winding arrangement.

When the impedance fluctuation decreases, the fluctuation of the reactive power, which is obtained by the product of the impedance and current, is also reduced, thereby improving system stability. In addition to this effect of preventing power supply quality loss, the stress on the current limiting resistance value of OLTCs is reduced, and for this reason, the measure helps improve the reliability of OLTCs.

3.2 Downsizing of equipment

As mentioned above, voltage regulating transformers often use 107-tap OLTCs. To achieve a107-tap configuration, conventional OLTCs used wire connection with 6 section coarse taps and 18 section fine taps.

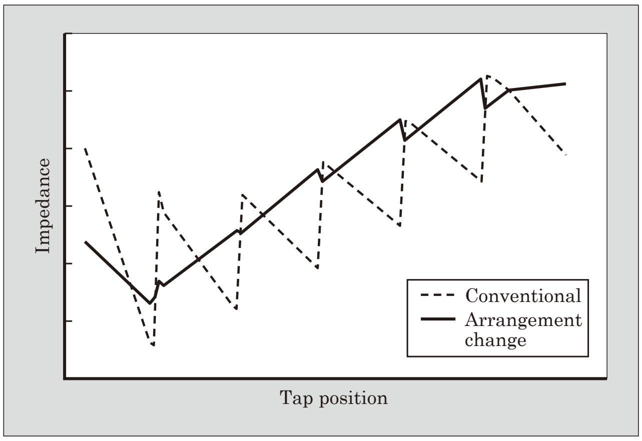


Fig.3 Example of change in impedance between primary winding and secondary winding

For the latest equipment, we have changed the fine taps from the upthrust method (method to add voltage to the coarse taps) to the hanging method (method to subtract voltage from the coarse taps) to obtain a wire connection of five section coarse taps, reducing the product size. This measure has reduced the size of the transformer to 88% that of the conventional product.

Figure 4 shows a skeleton diagram of the latest voltage regulating transformer, and Fig. 5 is a comparison between the tap structures.

3.3 Highly reliable design (Prevention of dielectric breakdown)

The receiving voltage of aluminum smelting equipment in recent years is generally approximately 220 kV, which is the highest voltage class for industrial-use transformers. For this reason, the intermediate voltage is also high. Figure 4 shows the skeleton diagram of the voltage regulating transformer. Its secondary winding consists of more than one coarse tap and one fine tap to form 107 taps, and has greater number of terminals than typical transformers. Therefore, to prevent dielectric breakdown in the secondary winding, the insulation design must be based on the accurate voltage oscillation and electric field distribution at each terminal as well as the terminals with voltage to be applied. The following are typical analysis examples:

(1) Voltage oscillation analysis

We used self-developed program based on an voltage oscillation analysis to estimate the transfer voltage and voltage distribution at each terminal of the secondary winding when 220 kV was applied to the primary winding (1U, 1V, 1W) and the voltage distribution at each terminal of the secondary winding when it was applied to the secondary winding (2U). As an example, Fig. 6 shows an example estimate of the voltage distribution. Figure 6 shows the applied waveform between the 2U terminal and GND when applied to the secondary winding (2U) and the voltage generated between the A23 terminal and GND, calculated by applying certain insulation design conditions. The voltage generated between the A23 terminal and GND is below 100% for all time periods. From this, we can determine that no dielectric breakdown was caused due to the application, and that the applied insulation design conditions are effective. From such analysis, the insulating distance and insulating paper thickness required for the secondary winding and terminal have been ensured to prevent dielectric breakdown.

We measured the voltage distribution when the manufacturing was completed and confirmed that the analysis results and actual measured values were almost the same.

(2) Electric field analysis

By entering the voltage at each terminal based on the analysis results above into the self-developed program for finite element method, we simulated the electric field distribution and strength at each winding part. Figure 7 shows an example of electric field

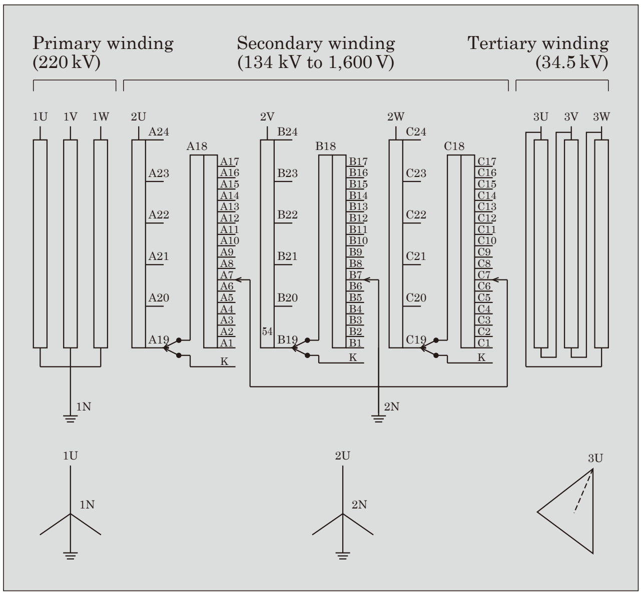


Fig.4 Skeleton diagram of voltage regulating transformer

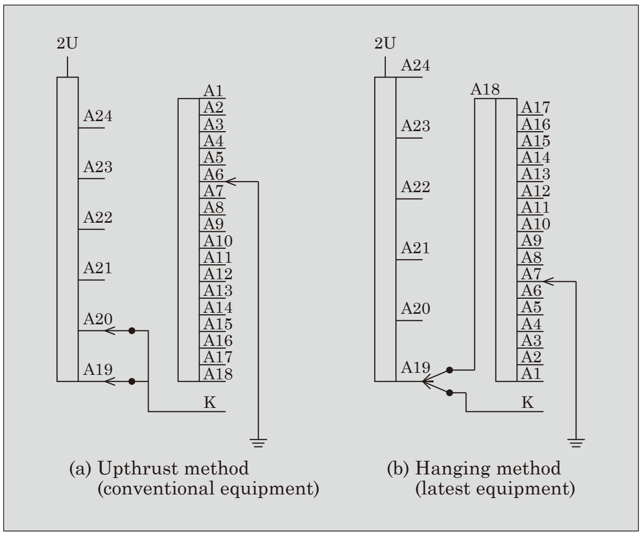


Fig.5 Comparison between tap structures

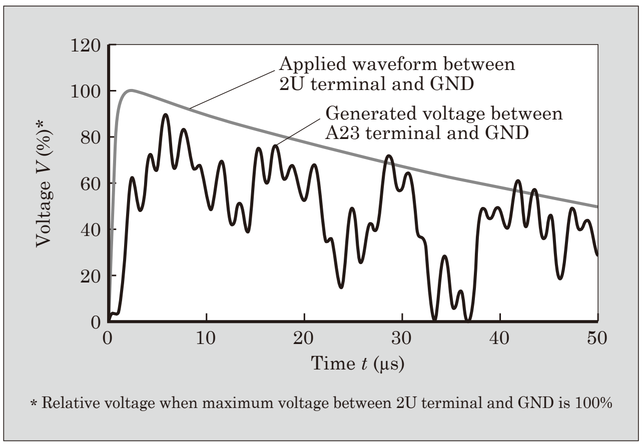


Fig.6 Estimate example of voltage distribution

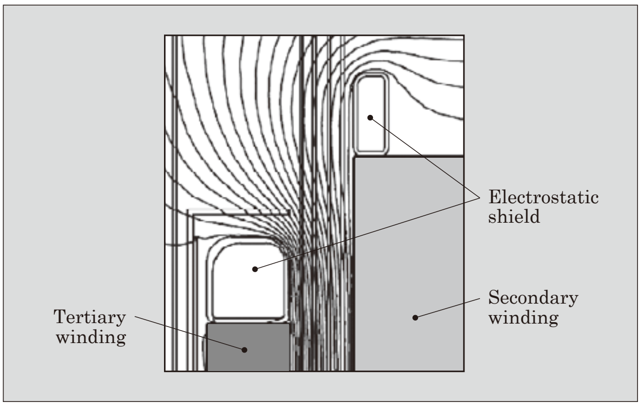


Fig.7 Example of electric field distribution between secondary winding and tertiary winding

distribution between the secondary winding and tertiary winding. We simulated the electric field strength between each terminal, in addition to between the secondary and tertiary windings. We thereby confirmed that the electric field strength at each part was lower than the allowable value, demonstrating that the design is capable of securing the necessary insulation distance without fail.

We also performed magnetic field distribution analysis, impedance calculation, mechanical strength calculation, and eddy current loss calculation at each tap to reflect the results in the design, satisfying customer requirements for the tank temperature, impedance, short-circuit strength and loss.

4. Efforts for Rectifiers

As rectifiers are used with higher currents, it is necessary to implement measures to prevent internal short-circuit accidents, as well as to minimize damage in the event of an accident.

4.1 Preventive measures for internal short-circuit accidents in rectifiers

If an abnormal current (overload, over-current, short-circuit and cross current) flows into a rectifier semiconductor, the pressure in the semiconductor increases. If the semiconductor case cannot withstand the internal pressure, it ruptures and emits gas into the rectifier cubicle (a volume of 38.3 m^3). Following are measures taken against such accidents:

(1) Protection of rectifier semiconductors using fuses

To protect rectifier semiconductors from the abnormal current and minimize effects on other semiconductors, fuses have been connected in series. The fuses are required to meet the voltage and current specifications of the rectifier and have the capability to fast interrupt abnormal current before the semiconductor case ruptures. In particular, since aluminum smelting equipment uses a high current, we perform verification tests to confirm the interruption performance of the fuses. Figure 8(a) shows the test circuit in the verification test, Fig. 8(b) shows an semiconductor simulation short-circuit test system consisting of an semiconductor and fuses for semiconductor protection, Fig. 8(c) shows a short-circuit current waveform and Fig. 8(d) shows a current waveform at the time of fuse interruption. When the short-circuit current (254 kA at the maximum) shown in Fig. 8(c) flows into the test circuit, the current is interrupted by the fuses for semiconductor protection, but the current remains flowing into

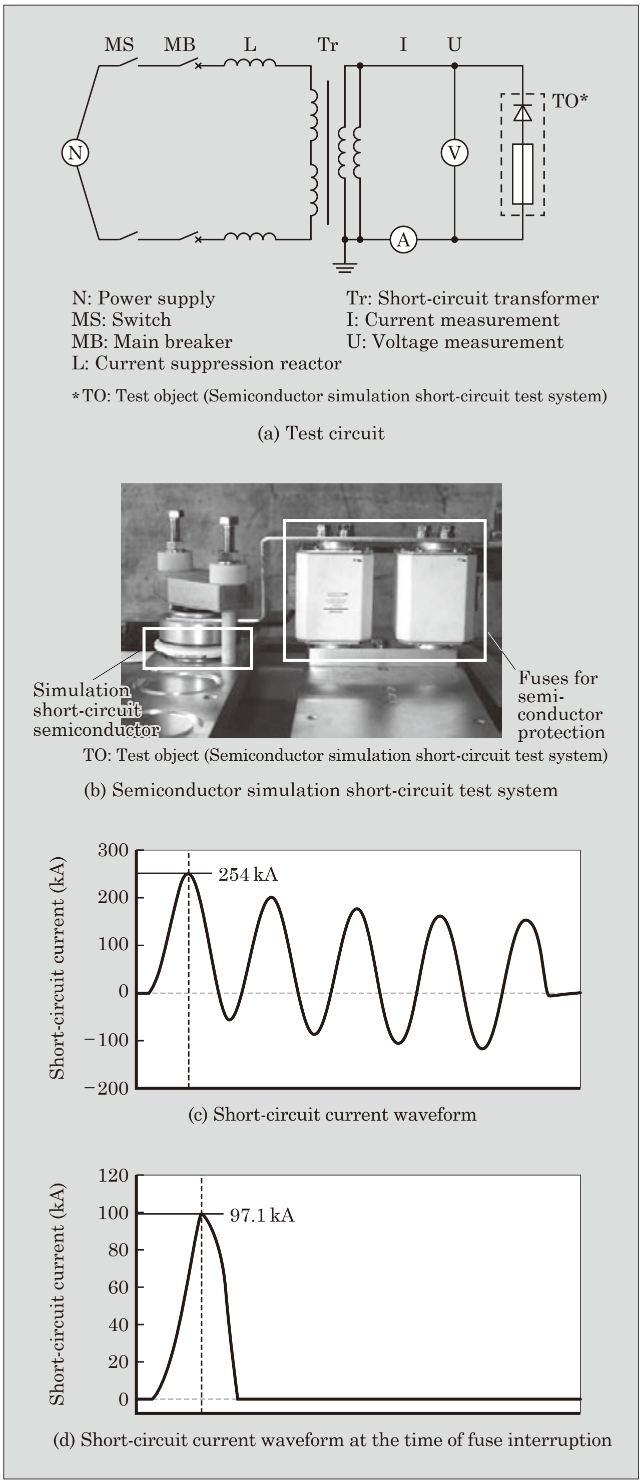


Fig.8 Verification test

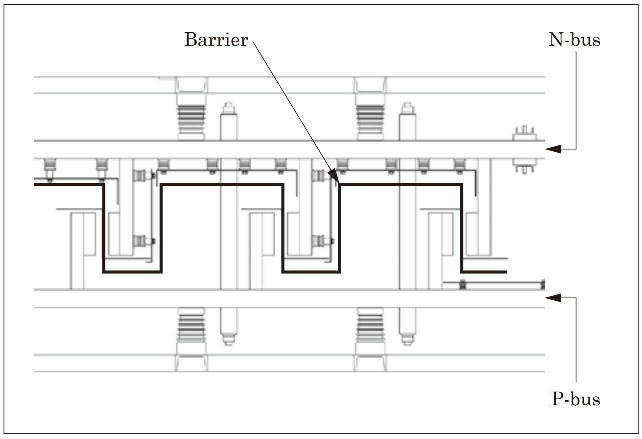


Fig.9 Arrangement of barrier between poles (plane view)

the semiconductor during the period until interruption as shown in Fig. 8(d). Since the interrupting current value is limited at 97.1 kA and lower than 99.5 kA, which is the breakdown current, the semiconductor case does not rapture.

(2) Prevention of internal short-circuit accident by installing barriers

Figure 9 shows the barrier inserted between the main circuit conductors (P and N buses) to physically isolate them to prevent internal short-circuit accidents caused by gas emitted into the rectifier cubicle when the semiconductor case ruptures due to abnormal currents.

4.2 Preventive measures for damage to rectifier cubicles in the event of an accident

Sufficient preventive measures have been taken for internal short-circuit accidents in rectifiers, but to prevent damage due to internal pressure increase in the event of an internal short-circuit accident, pressure relief devices have been installed on the ceiling part of the rectifier. We adopted the following manner to analyze and evaluate whether there was damage to the rectifier cubicle during the operation of the pressure release device releasing the internal pressure out of the cubicle.

(1) Calculation of the internal pressure increase value in the rectifier cubicle

Figure 10 shows the arc energy and internal pressure increase. Figure 10(a) shows the established analysis model, which assumed that the position at which the distance between the main circuit conductors was shortest was to be the starting point of the short circuit (short-circuit point). First, we calculated the generated energy (arc energy) from the relationship between the distance from this short-circuit point and the short-circuit current generated at the rectifier operation point. Next, we estimated the pressure change that occurs when the arc energy raised the air temperature in the cubicle. As a result, as shown in Fig. 10(b), the values for the main circuit compartment, disconnector compartment and cubicle cooling compartment were

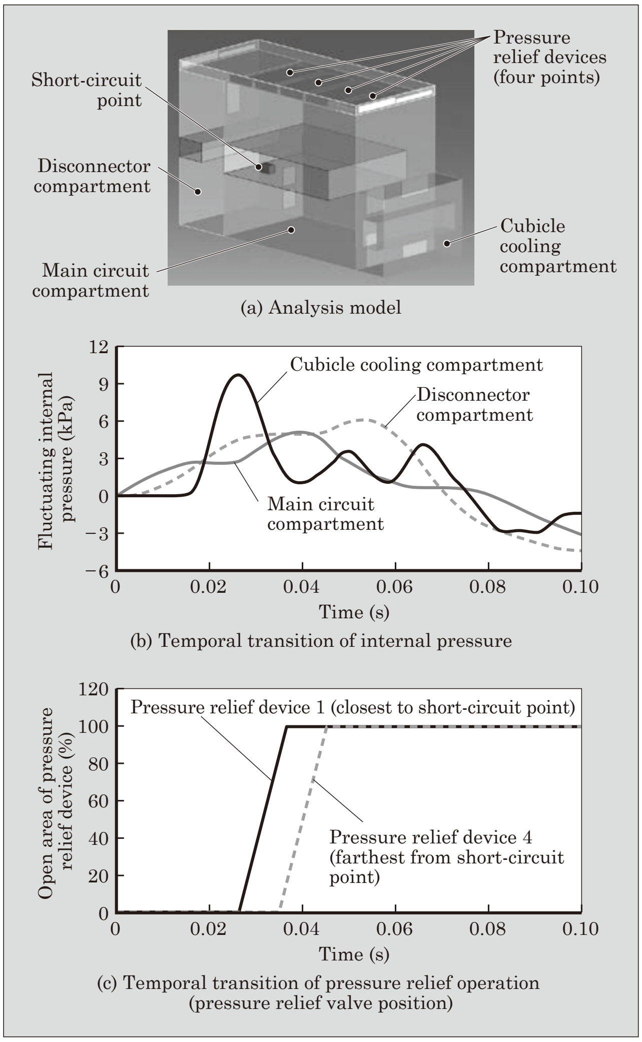


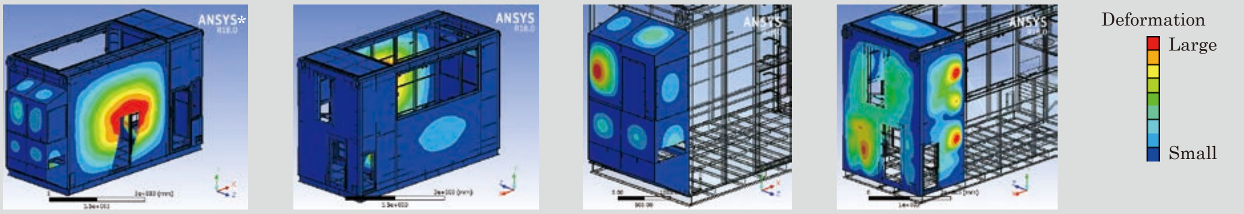
Fig.10 Transition of arc energy and internal pressure increase

all lower than the target of 10 kPa. As shown in Fig. 10(c), pressure relief device 1, which is closest to the short-circuit point, was activated at approximately 0.03 s following the short circuit, and pressure relief device 4, which is farthest from the short-circuit point, was fully opened after approximately 0.05 s following the short circuit. The pressure relief devices activated within such a short time thereby suppressed the pressure increase in the cubicle.

(2) Analysis of stresses on rectifier cubicle

For the increase of the internal pressure described above, the stresses applied to the wall surface of the rectifier cubicle were analyzed, and the deformation of the rectifier cubicle was confirmed from the stress. Figure 11 shows the results of the stress analysis of the rectifier cubicle used to confirm the amount of deformation. The red points in the figure are parts where significant deformation was seen. We confirmed that the amount of stress (400 MPa or less) was not enough to cause damage.

As a result, we confirmed that even if a short circuit occurred in the rectifier, the rectifier cubicle would not be damaged because the pressure release device



222.3 MPa maximum (a) Front of rectifier cubicle | 74.1 MPa maximum (b) Back of rectifier cubicle | 395.6 MPa maximum (c) Front of rectifier cubicle | 288.0 MPa maximum (d) Back of rectifier cubicle

*Ansys: Trademark or registered trademark of ANSYS Inc.

Fig.11 Results of the stress analysis for the deformation of the rectifier cubicle

would operate to release the internal pressure out of the cubicle before the rectifier cubicle ruptured.

5. Countermeasures Against Harmonics for Transformer Rectifiers

Aluminum smelting facilities are generally structured with redundant AC power supplies and harmonic filters as well as transformer rectifiers. However, in recent years, the AC power supplies of transformer rectifiers has become complicated, and they often receive power from off-premises commercial power sources in addition to on-premises private generators. Therefore, multiple operation pattern exists in a power supply system, and the harmonic impedance on the AC power supplies when seen from the transformer rectifier fluctuates in each case. In addition, the amount of harmonics generated is increasing as equipment capacity increases.

Fuji Electric is continuing to develop system analysis technologies to predict local harmonic generation more accurately. In particular, for transformer rectifiers for aluminum smelting equipment, we are making efforts to refine the following analysis models using general-purpose system analysis software typified by EMTP-RV*1:

(a) Multi-pulse rectification model with multiple units (72-pulse rectification)
(b) Integrated control algorithm for multiple units
(c) OLTC model and voltage regulating reactor model

In addition to these, by modeling power supply systems and DC load equipment, it has become possible to precisely predict local operation conditions and estimate the generation of even harmonics and Untheoretical harmonics due to three-phase unbalance, which had been difficult to do in the past.

6. Postscript

This paper described industrial-use power supplies that contribute to the stable operation of material manufacturing equipment. Transformer rectifiers are also necessary for the manufacturing of material products such as green hydrogen, which has been on the rise in recent years, and we believe that they will become increasingly important in the future. We will continue to utilize the technologies cultivated by Fuji Electric to contribute to efforts for the realization of a low-carbon society.

*1 EMTP-RV: It is an acronym for the Electro Magnetic Transient Program-Restructured Version and instantaneous value analysis program for the power system. EMTP is a trademark or registered trademark of the EMTP Alliance.

Fuji Electric

Innovating Energy Technology