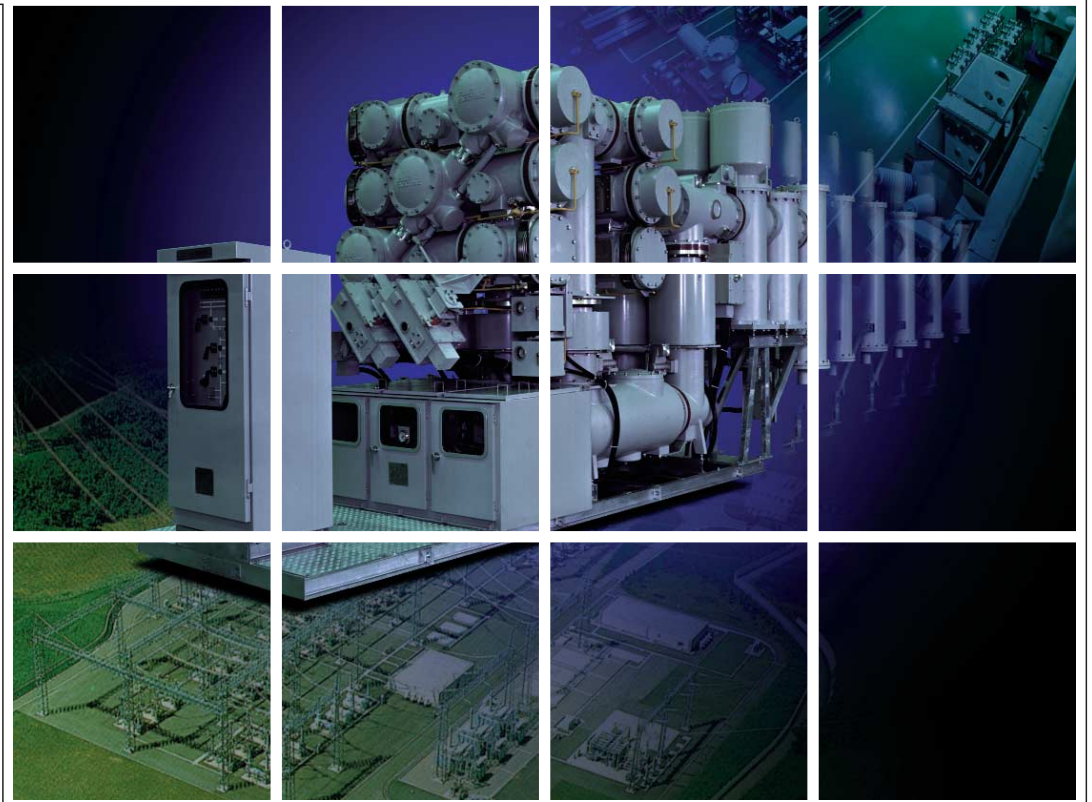


# FUJI ELECTRIC REVIEW



1999 VOL.45

## Substation Equipment Technologies



# With Trustworthy Technology,

Fuji Electric as a manufacturer of comprehensive substation equipment is ready to supply advanced gas-insulated switchgear (GIS) superior in reliability, disaster prevention, safety and environmental harmony.



72.5kV three-phase-encapsulated GIS



123/145kV phase-segregated GIS



170kV three-phase-encapsulated GIS



245/300kV phase-segregated GIS

## ● Compactness

Reduction in size and weight with compound components and rational layout contributes to reduction in the area and period for installation.

## ● High safety

The safe construction completely enclosing live parts eliminates fear of electric shock and fire. The GIS combined with gas-insulated transformers can make a totally gas-insulated substation.

## ● High reliability

The latest technology utilized under the utmost quality control system based on ISO9001 ensures high reliability and quality from the factory to sites.

## ● Environmental harmony

Careful consideration is given to environmental harmony, such as reduction in the installation period of power stations and substations and harmonious design with the surrounding scene.

## ● Ample types

Ample types from 72.5 to 300 kV are prepared to meet various needs.

# FUJI ELECTRIC REVIEW

Substation Equipment Technologies

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### Cover Photo:

Substation technology has made advances in increase in unit capacity, downsizing, environmental harmony and economical efficiency as well as in reliability enhancement and performance improvement.

Fuji Electric has achieved downsizing and rationalized transportation and installation using advanced technologies such as large transformers for thermal power stations capable of fully assembled transportation, extra-high-voltage gas-insulated switchgear (GIS) and on-site-reassembled transformers fit for transportation limits. The development of new high-performance digital protective relays and substation supervision systems using local area network (LAN) has contributed to the stable supply of electric power.

The cover photo with a factory clean room and a substation on site for a background shows extra-high-voltage GIS transported between them in a fully assembled bay.

# Present Status and Prospects for Substation Technology

Ikuo Sadakawa  
Hideo Kaneko  
Toshio Matsumoto

## 1. Introduction

In our present society that is greatly dependent on electric power, substation technology plays an important role in the stable and high-quality transmission of electric energy. Advances in substation equipment technology have led to increased unit capacity, smaller size, and environmental preservation. To meet the demand for power system operation with high reliability, technology for protection and control systems has progressed toward advanced protection and control utilizing recent electronics and enhanced reliability. This paper describes the trends of substation technology, Fuji Electric's efforts in this field, as well as future prospects and problems.

## 2. Trends of Substation Equipment Technologies

### 2.1 Transformer

#### (1) Increasing voltage and unit capacity

Since Fuji Electric started manufacturing transformers in 1923, we have striven to raise the voltage and unit capacity of oil-immersed transformers. The transition is shown in Fig.1. Fuji Electric began supplying ultra high-voltage transformers to the Bonneville Power Administration, USA in 1968, and has since supplied many units in Japan and abroad, including autotransformers of 765kV, 2,000MVA (bank) to the ESKOM, South Africa in 1986. The total number, supplied by Fuji Electric, of ultra high-voltage transformers having a lightning impulse withstand voltage of 1,300kV or more is 77 banks, 48,377MVA.

Regarding 500kV power transformers for domestic power companies, since the delivery of a 525kV, 1,000MVA (bank) to the Seiban Substation of The Kansai Electric Power Co., Inc. in 1980, we have supplied 10 banks, 8,390MVA in total.

As for step-up transformers for thermal power stations, we made efforts to develop technologies for large capacity transformers and delivered a 280kV, 1,100MVA transformer to the Higashi-Ogishima Power Station of The Tokyo Electric Co., Inc. in 1990.

(2) Technologies to increase efficiency of large capaci-

ty transformer

Fuji Electric has supplied complete-bank-transportable transformers utilizing low-noise and all-tank technologies for large capacity step-up transformers in thermal power stations. For installation in a power station or substation in a mountainous region with difficult transport conditions, a FATRAS (Fuji advanced transformer reassembled at site) was supplied.

The eight 281.25kV, 380MVA transformers supplied to the Chiba Power Station of The Tokyo Electric Power Co., Inc. utilize the latest low-noise technology and were transported in a complete bank, increasing the efficiency of transportation and onsite installation.

The use of step-lap joint cores and anti-vibration steel plates for transformer tanks reduced noise from the transformer unit and the soundproof wall was omitted (noise level: 65 dB). Further, a well-balanced arrangement of accessories including coolers made it possible to transport the transformer in a complete bank that was pre-assembled at the factory. As the result, the onsite installation time decreased by 30%

Fig.1 Transition of the maximum voltage and unit capacity of oil-immersed transformers

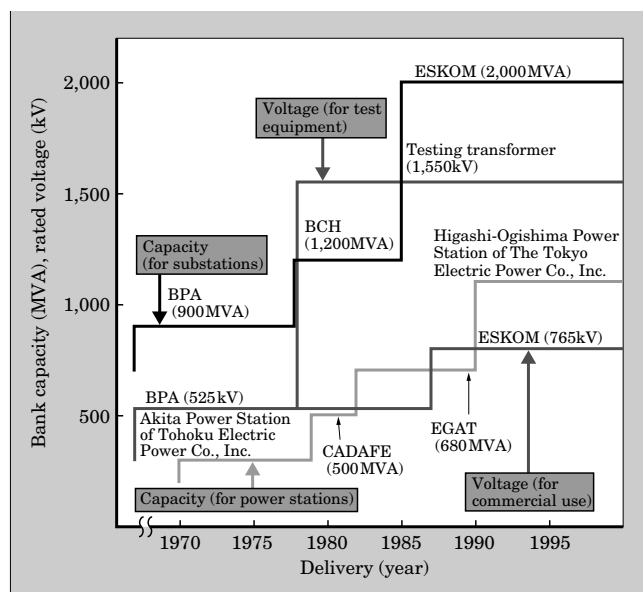


Fig.2 Main transformer being transported in a complete bank



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and reliability improved. Figure 2 shows the transformer being transported in a complete bank.

Additionally, six 275kV, 265MVA transformers were supplied to a domestic thermal power station. In the past, the main and station service transformers of this type had been manufactured and installed separately. However, in this new construction, both cores and windings were contained in a single tank, and the coolers, mechanical protective devices, and monitoring instruments were shared. This resulted in reduced installation space, a reduced number of foundations and soundproof walls, simplified transportation, fire fighting equipment, and isolated bus ducts, and decreased the onsite installation time.

As for onsite reassembled transformers, a 275kV 250MVA unit for the Shin-Hokushin Substation of Chubu Electric Power Co., Inc. and a 275kV 100MVA unit for the Ugo Substation of Tohoku Electric Power Co., Inc. were supplied. These units were manufactured, tested, inspected, and then disassembled into transport units at the factory. Finally, they were transported to the site by trailer, reassembled, and then tested.

The core and winding were separately transported. The core was secured with transport fixtures to prevent distortion and slippage during transport. The winding was packed with high polymer films to protect against moisture and dust during transportation and onsite installation.

Technologies developed for onsite-reassembled transformers have made it possible to select a transformer construction (non-segregated tank, special three-segregated tank, or onsite-reassembled type) corresponding to different site transportation conditions that can reduce the total cost including transportation cost.

### (3) Anti-disaster type transformer

SF<sub>6</sub> gas-immersed or cast resin transformers are highly rated because of their safety, which is improved due to their nonflammable or flame-retarding charac-

Fig.3 Liquid-nitrogen-cooled, single-phase, 500kVA superconducting transformer



teristics. These types of transformers are increasingly used in urban substations.

Fuji Electric has developed SF<sub>6</sub> gas-immersed transformers since 1973. The most recent shipment was a 110kV, 40MVA unit to the Shimada Substation of The Chugoku Electric Power Co., Inc. Fuji Electric has delivered 199 units (1684.6 MVA) thus far.

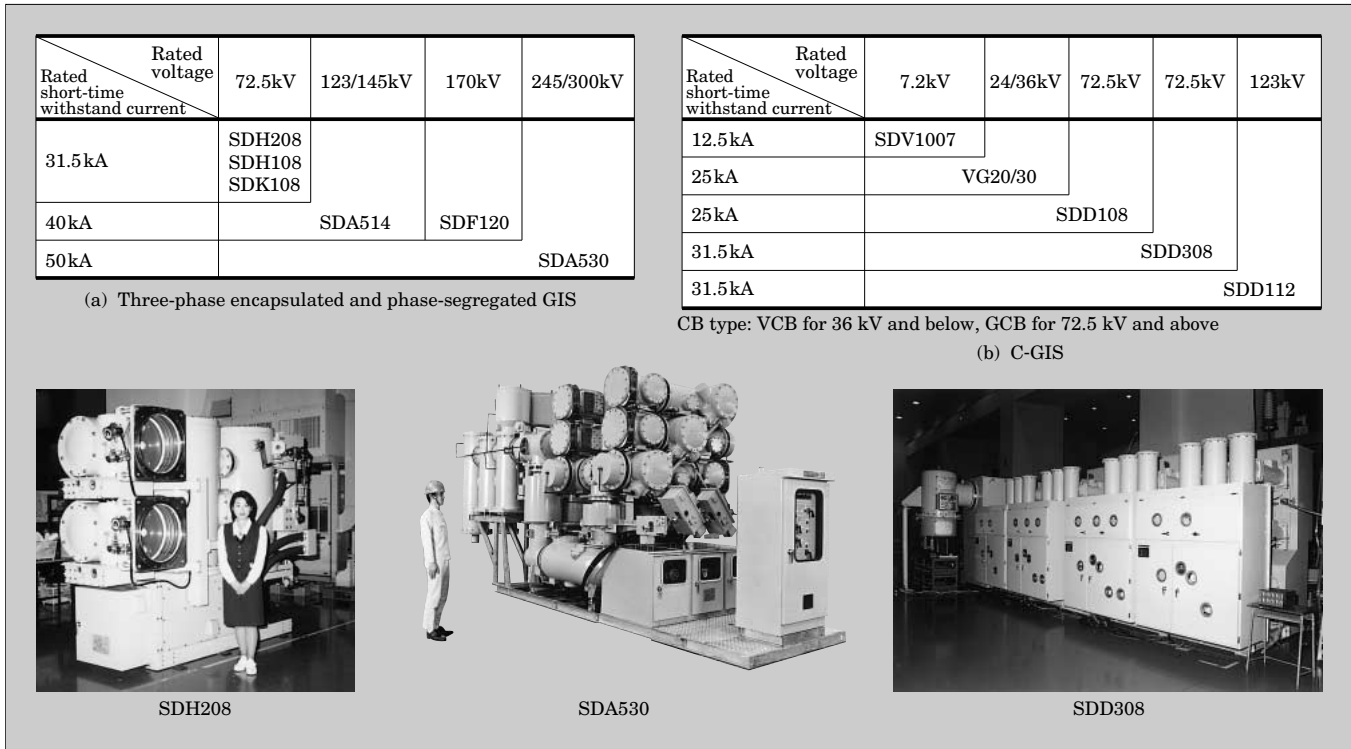
Fuji Electric has made SF<sub>6</sub> gas-immersed transformers more efficient with such industry innovations as application of a high-head radiator with high cooling efficiency to the cooling system. To develop larger capacity units, in 1997, we developed a prototype of a forced-gas-directed, forced-water-cooled (GDWF) single-phase, 66kV, 60MVA SF<sub>6</sub> gas-immersed transformer and verified satisfactory results. Combining this with our previous production experience, we have established the technology for 154kV, 60MVA class SF<sub>6</sub> gas-immersed transformers. Using an electronically controlled operating mechanism, a 1,600A on-load tap changer with a 4-vacuum switch, 2-resistor system realized high reliability and a long life span.

Fuji Electric began manufacturing cast resin transformers in 1970. As the leading domestic manufacturer of cast resin transformers, Fuji Electric manufactured a 13,000kVA unit of the largest capacity class in Japan, and thus far, the total number of manufactured units has exceeded 50,000. Since Fuji Electric started manufacturing cast resin transformers, it has consistently made encapsulated windings formed with a metal mold using sheet windings and a vacuum.

Fuji Electric in cooperation with Kyushu University developed a superconducting transformer attracting attention as a 21st century transformer. Although superconducting transformers still have technical and economical problems to overcome, they are attractive due to their great reduction in size and loss as well as non-flammability characteristics.

The prototype is a single-phase unit with a rated voltage of 6.6kV and rated capacity of 500kVA, using windings of bismuth oxide superconductors and liquid

Fig.4 Fuji Electric GIS and C-GIS product series



nitrogen cooling. The external view is shown in Fig. 3. This is the first application in the world that utilizes the high-temperature superconductivity of an oxide.

## 2.2 Switchgear

### (1) SF<sub>6</sub> gas circuit breaker

Fuji Electric developed a new 300kV, 50kA (single-breaking unit) SF<sub>6</sub> gas circuit breaker (GCB) (BAK830) in which the interrupting chamber makes effective use of arc energy; the current breaking capability and voltage withstand capability were improved and the parallel capacitor was omitted. Production began in 1997.

With regard to the GCB operating mechanism, Fuji Electric has used hydraulic operating mechanisms since 1974 and thus far has manufactured approximately 6,000 units, the majority of hydraulic units in Japan. By implementing advances such as pipe-less construction using a complete block unit system, we have stabilized quality.

With regard to 72.5kV GCBs, in addition to conventional hydraulic operating mechanisms, we developed a motor-charged-spring operating GCB (BAK808) and completed a product series for this type of GCB. The interrupting chambers for this series are constructed so as to have both a thermal puffer (self arc-extinguishing) system to effectively use arc energy at the time of current breaking and to raise the gas blast pressure, and a small mechanical puffer system for small current breaking. Dimensions of the interrupting chambers are reduced and also operating energy is decreased by half compared to the conven-

tional mechanical puffer system. The development of this high-performance interrupting chamber has made it possible to utilize the low-power motor-charged-spring-operating mechanism.

### (2) Gas-insulated switchgear

Fuji Electric has supplied gas-insulated switchgears (GISs) for approximately 3,000 circuits now in operation. We have made efforts to increase reliability and reduce size of the GIS, particularly those models with rated voltage of 204kV or less. To meet various user needs, GIS products have been developed with novel, unique ideas based on Fuji Electric's original component technology. Recently, a 245/300kV phase-segregated GIS and a new 72.5kV compact GIS have been added to the product series. The GIS and cubicle type GIS (C-GIS) product series are shown in Fig. 4.

The 300kV phase-segregated GIS (SDA530) developed in 1996 has been supplied to domestic power companies since 1998. This GIS was developed based on the concept of creating a transportable fully assembled bay, a feat not possible with the conventional three-phase-encapsulated 300kV GIS. During the development, advanced analysis technology such as three-dimensional electric field analysis and gas flow analysis was utilized. The total GIS size was reduced by utilizing components such as a new GCB without parallel capacitor, a high-performance lightning arrester, and a new compact voltage transformer. As a result, the GIS became smaller and lighter than the former three-phase-encapsulated type. Consequently, the total GIS size was reduced and transportation of a fully assembled bay on a trailer was realized. The



weight of a normal feeder bay is as light as 12 tons.

Transportation of a pre-assembled bay makes it possible to install a GIS, which was assembled and tested at the factory, intact in the substation. This improves quality and reduces by half the onsite installation time.

With regard to 72.5kV GIS, we developed a new compact type (SDH208) by integrating the component parts of the former three-phase-encapsulated compact GIS (SDH108, SDK108). A new interrupting chamber and a high-performance arrester were used for the components. By increasing the integration of equipment on the line side of the circuit breaker, the former three tanks were reduced to one tank. Compared to the former type, the installation area decreased to 57% and the volume to 42%; thus, great size reduction was realized. In particular, the bay width of 1,100 mm and the height of 2,300 mm reached dimensions nearly equal to that of 6kV cubicles. This great reduction in size enabled the transportation of five bays of GIS on a single trailer, resulting in a reduction of the installation time as well as the installation space.

### (3) Lightning arrester

The lightning arrester (LA) use zinc oxide (ZnO) elements developed by Fuji Electric. Recently, to meet requirements for efficient insulation coordination and equipment downsizing, high-performance LAs with lowered residual voltage levels have been used.

Fuji Electric developed high-performance ZnO elements with increased reference voltage by using fine-grained ZnO crystals. A product series of tank type LAs for 66kV to 275kV circuits using these elements has been completed. The high-performance element can raise the reference voltage from 200V to 300V per mm of the element, and therefore the element thickness can be decreased to approximately 2/3 that of the former element.

Formerly, the element arrangement for a 154kV or 275kV LA was of a three-pole construction. However, with thin elements, a simple single-pole construction can be used. This high-performance LA has been applied to the newly developed 300kV GIS and the new compact 72.5kV GIS, and has contributed to the GIS downsizing.

## 2.3 Trends of substation protection and control technologies

### (1) Protective relay systems

Approximately 15 years have passed since the introduction of digital protective relays. Fuji Electric's first product with the basic series code DUC was developed in 1983. At that time, CPUs mounted with relays were 16 bits, ran at 6MHz, and used assembly language due to restricted computation speed. However, since they possessed sufficient advantages of digital relays, such as stable relay characteristics due to reduced analog parts, improved operation reliability with a self-diagnosis function, and a greatly reduced

installation area, their use spread widely as these advantages were recognized. Thereafter, Fuji Electric developed the DUF series in response to progress in microcomputer technologies and requirements for power system protection. The DUF series used a 32-bit CPU, ran at 16MHz, and used C language widely. The use of C language greatly contributed to improved development efficiency and reliability. The DUF used a digital signal processor (DSP) and high-speed sampling for the analog input device, and greatly increased the amount of digital processing for the filtering functions. Formerly, even digital relays depended on analog elements for filter functions such as the elimination of harmonic components. Characteristics of these analog elements fluctuated over time and remained a weak point of the DUC series; however, this disadvantage was overcome by expanding the digital functions. Analog filters required different characteristics to match the relay elements. Through the increase in digital filter processing, hardware standardization was attained, and increased sampling frequency (eight times the former) led to the development of a new high-level protective algorithm. Thereafter, conditions related to protective relay systems required the following new developments.

- Advanced basic performance of digital relays by aggressively introducing the latest hardware technology, and improved price-to-performance ratio
- Increased sophistication of the functions of supervision and automatic inspection, and improved reliability of equipment operation
- Promotion of labor reduction and enhanced efficiency in operation tasks such as equipment maintenance and inspection, setting, and supervision, including remote operation
- Facilitation of easy analysis of the status when a relay system actuates, quick restoration of the circuit or system by locating the fault, and the use restoration guidance at the time of a system fault
- Introduction of serial communication technology such as a LAN to realize high-speed, space savings, and low-cost data communication between equipment inside and outside a substation

The specifications of second-generation digital relays (DUG series) developed based on these general ideas in comparison with the specifications of Fuji Electric's former digital relays are shown in Table 1.

### (2) Substation supervisory control systems

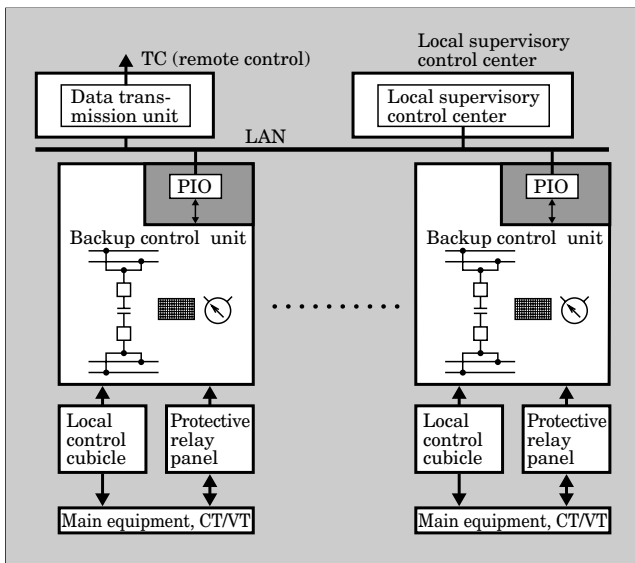
Substation supervisory control systems have made technical progress due to the application of microcomputer technology, coordination of advanced functions, performance of supervisory control and data acquisition systems (SCADA), application of LAN technology, and adoption of advanced human interface technology for monitoring and control. Recent substations have various system configurations according to the degree that the above technology is utilized, the user's policy toward standardization, and the substation's unique

Table 1 Second-generation digital relay system (compared to conventional systems)

Classification Item		Conventional digital relay		Second-generation digital relay
		DUC	DUF	DUG
Main processor		16-bit CPU (6 MHz)	32-bit CPU (16.6 MHz)	32-bit CPU (50 MHz)
Processing speed		1.0 (reference)	3.0	10.0 or more
Analog input	Sampling frequency	600Hz/720Hz	4,800Hz/5,760Hz	4,800Hz/5,760Hz
	A-D converter	12 bits	12 bits	16 bits
	Input filter	Analog	Analog & digital	Analog & digital
Human interface		Panel-mount type (LED & digital switch)	Panel-mount type (LED & 10-key switch)	Portable PC or panel-mount flat display
Language		Assembler	C language	C language
Fail-safe unit	CPU	16-bit CPU	16-bit CPU	32-bit CPU
	AI	600/720 Hz, 12-bit A/D, 4 channels	600/720 Hz, 12-bit A/D, 8 channels	4,800/5,760 Hz, 16-bit A/D, 12 channels
	DI/DO	8 inputs/8 outputs	8 inputs/8 outputs	8 inputs/8 outputs
Automatic supervision		With simple retry inspection	With simple retry inspection	With frequency supervision, CPU restart, retry inspection, etc.
Data saving/analysis support		Fault record memory	Fault record memory, analog data when power system fault occurs, and relay operation memory	Failed part memory and display, data when power system fault occurs, and relay operation memory
Remote operation		—	—	Remote setting, supervision, diagnosis, and analysis (through Ethernet* LAN)

\*Ethernet: A registered trademark of Xerox Corp., USA

Fig.5 Block diagram of a digital supervisory control system



conditions. This paper describes recent trends, shown in Fig. 5, based on actual examples of Fuji Electric's experience. Digital supervisory control panels that are installed in bay units are mounted with a set of functions required by the bay (supervision, control, metering, synchronizing, etc.). In former supervisory control systems, because panels were constructed for each function, there was much data communication between panels. In the new system configurations, panels each for a bay unit are independent (with limited communication), have improved maintainability, are standardized, and prevent panel faults from

affecting other panels. Data communication between supervisory control panels and SCADA and between supervisory control panels and protective relay panels are connected by serial interfaces such as a LAN. The use of a LAN makes possible small, simple system configurations without increasing the number of cables, and eliminates interfaces for the former auxiliary relays. Various protocols and speeds of serial interfaces and LANs are used according to the level of system requirements. A CRT display or equivalent is used to monitor and control substation data.

### 3. Future Substation Technology

There have been great changes in the social environment such as the information-orientation of society and environmental problems, including global warming.

In response to such changes in society, it is necessary to make positive efforts to enhance the reliability, lower the cost, and increase the environmental friendliness of substation equipment.

- (1) Cost reduction of substation equipment by reducing size and increasing transport efficiency

Fuji Electric is ranked as an industry-wide top-class manufacturer of small-size and lightweight GIS of 300kV and below. GIS downsizing technology is considered to be nearly matured. In the future we will strive to develop and improve GIS components, GCB, LA, CT/VT, etc., and to examine methods of further downsizing, leading to higher reliability and lower cost.



With regard to transformers, we have achieved total cost reduction, including the transportation cost, by applying a complete-bank-transportable type or onsite reassembled type to extra-high-voltage transformers. In the future, onsite reassembled transformer technology will be applied to larger capacity, higher voltage transformers. Methods to further improve the quality of assemblies onsite and increase the efficiency of onsite construction are topics of future study.

It is also necessary to understand substations from the viewpoint of a system or a plant, and to plan for total cost reduction throughout the entire engineering process by coordinating the design of the power system and equipment, layout, specifications, construction, transportation of equipment, operation, maintenance, etc.

#### (2) Distributed substation supervisory control systems

Problems of protective relay systems related to power systems and advanced operating functions for control systems such as operation support and maintenance support remain as important topics. However, the most important topic of future substation supervisory control systems will be total cost reduction. To date, the technical transition in this field is such that technology and the efficiency of individual equipment has advanced, and currently, the digitization of SCADA, control and protective equipment, and integrated digitization via serial communication are in development. When viewed from the standpoint of cost reduction, it is necessary to optimize the entire substation, including the control systems and sensors mounted on main equipment such as on the GIS and transformers. To pursue total cost reduction, such as the simplification of maintenance and inspection work, reduction in onsite construction costs, and reduction in substation site area including the control building, it is desirable that substation supervisory control systems are distributed around the equipment and perfectly connected with other equipment (SCADA and protective equipment) via high-speed serial communication.

#### (3) Operation and maintenance technology

Maintenance support systems have been introduced to eliminate patrol and inspection in substations, to prevent faults from occurring, and to provide support in case of an emergency. Equipment operation data is input to the maintenance support system by sensors mounted on the equipment. More than ten years have passed since sensors were first mounted on the equipment, and due to improvement in sensors, their practical performance have been recognized even in severe field applications that encounter harsh outdoor environments and noise. Total cost reduction, including sensors, transducers and the upper system, remains a problem to be solved.

Fuji Electric took the initiative to develop greaseless 7.2kV vacuum circuit breakers and on-load tap

changers by applying a special coating treatment to parts of the operating mechanism as well as to realize a contact-free control circuit. The application of these improvements to products has simplified maintenance and inspection. Labor saving maintenance and inspection, efficient inspection, and the prolongation of service life will remain desired in the future and further efforts for improvement are necessary.

#### (4) Power electronics technology

Fuji Electric has applied power electronics technology to various fields.

Power electronics technology has been applied to uninterruptible power systems (UPS), inverters for motor drive, rectifiers for chemical plants, induction heating, and flicker compensators in the industrial field, as well as to driving converters for trains and rectifiers for electric railways in the transportation field. Recently, this technology has been applied to fuel cells, solar power generation, and converters for power system interconnections that are used for power storage batteries. In the future, applications will be extended to superconducting magnetic energy storage (SMES), flexible AC transmission systems (FACTS), and power distribution equipment.

Problems in applying power electronics technology to power systems include increasing the voltage and current of power semiconductors, stabilizing system operation with sophisticated controls, and improving compactness, efficiency, and reliability of the products.

#### (5) Environmental measures

To reduce transformer noise, step-lap joint cores and anti-vibration steel plates have been used. In the future, regulations against noise will become stricter. The study of anti-vibration techniques for tank walls is necessary to reduce noise.

In the "United Nations Framework Convention on Climate Change, the Conference of the Parties on its Third Session" (COP3) held in Kyoto in December 1997, SF<sub>6</sub> gas was specified as a greenhouse effect gas that would influence global warming. To decrease the amount of SF<sub>6</sub> gas used, a new product should be developed based on the concept of small size with less SF<sub>6</sub> gas.

To realize environment-friendly substation equipment, it is necessary to reduce the size, weight, and loss of the equipment, and in addition, to consider easily recycled materials and constructions.

## 4. Conclusion

The developing trends of substation technology and Fuji Electric's related efforts thus far have been described. We will continue to develop technology for substation equipment and systems to provide a stable supply of higher quality power and reduce the total cost of transmission and distribution equipment.

# Extra-High-Voltage SF<sub>6</sub> Gas-Insulated Switchgear

Shuichi Sugiyama  
Masahiko Fujita  
Takahiro Shinohara

## 1. Introduction

Due to location criteria and toughened restrictions on transportation, it has become increasingly difficult over the past several years to secure sites for substations. Consequently, the development of smaller-sized SF<sub>6</sub> gas-insulated switchgear (GIS) has been eagerly awaited.

In accordance with these needs, Fuji Electric has recently developed a small-size lightweight 245/300kV phase-segregated type GIS (model: SDA530) that can be transported fully assembled. This paper will introduce the construction, special features and test results of this GIS.

## 2. Details of Development

Figure 1 shows the external view of the SDA530 type GIS. This GIS has a phase-segregated construction in which the busbars are located in front, the line-side equipment of the circuit breaker (CB) is at the back, and the CB is arranged horizontally at the bottom.

Fig.1 An outside view of the 300kV phase-segregated type GIS

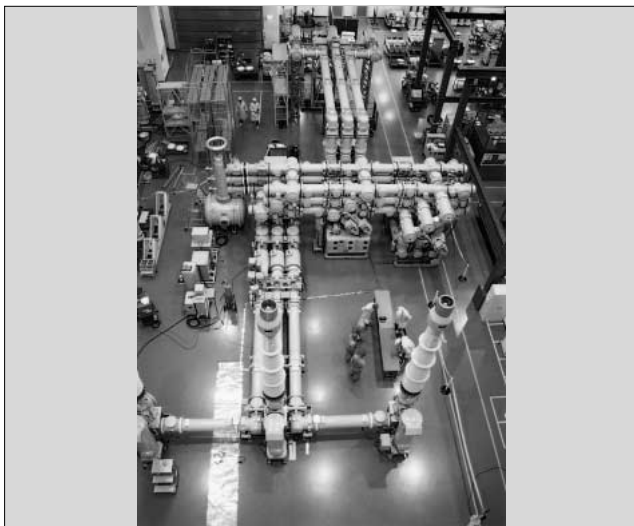
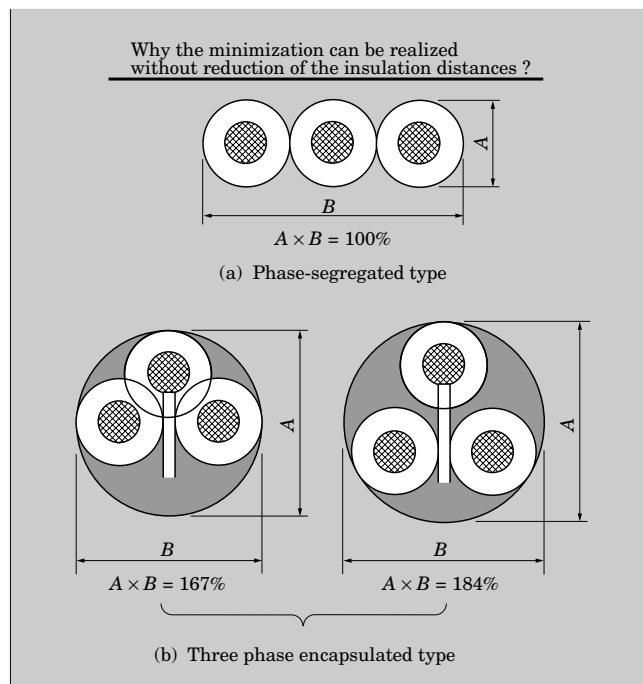


Figure 2 shows a comparison of space factors between a phase-segregated type GIS and a three-phase encapsulated type GIS with the assumption that the busbar diameter and the insulation distance are equal for both of these two types. It is obvious from Fig.2 that the phase-segregated type has a higher space factor and therefore has greater potential to be made smaller with a new design.

Fuji Electric recognized this point, and in 1989 first developed a small and lightweight 145kV phase-segregated type GIS (model: SDA514) with a new conception. The new 300kV phase-segregated type GIS (model: SDA530) was developed to be transportable after full assembly. The construction of the SDA530 is basically similar to that of the SDA514 type GIS, however by introducing the latest equipment technology, a noticeably smaller size and lighter weight have been realized.

Fig.2 Comparison of the space factors



### 3. Ratings and Specifications

The major ratings and specifications of the newly developed GIS are listed below.

- (1) Rated voltage: 245kV, 300kV
- (2) Rated normal current: 2,000/3,150/4,000A
- (3) Rated short-time withstand current: 31.5/40/50kA
- (4) LIWV: 1,050kV
- (5) Rated SF<sub>6</sub> gas pressure: 0.6MPa

The design was standardized for the 245kV and 300kV GIS. The rated normal current and the rated

short-time withstand current are unified at 4,000A and 50kA respectively, sufficient for almost all of the specified ratings in the marketplace. Consequently, development costs have been reduced and the economic benefits of standardization have been obtained.

### 4. Special Features

- (1) Small size and lightweight

Due to the utilization of such features as phase-segregated construction and aluminum alloy tanks, a remarkably small-size and lightweight has been obtained. Figure 3 shows the comparison of dimensions between the conventional three-phase encapsulated type (Fuji Electric's typical design) and the newly developed phase-segregated type. From this comparison, it can be seen that installation space is decreased to 58%, volume to 40% and weight to 50%.

- (2) Improved reliability

Because of the phase-segregated type construction, there is no occurrence of phase-to-phase short-circuits. Assembly is easy and centering is not necessary because of the simple and concentric structure of the conductor. Fully assembled transportation by trailer is possible, and the GIS may be installed in a substation in the same condition as it stood in the factory after assembly and tests. This stabilizes the quality control.

- (3) Improved maintenance and on-site inspection

Since the driving mechanism and gauges are all located in either the front or the rear areas, daily inspection and operation are possible from the front or rear spaces.

Fig.3 Comparison of dimensions

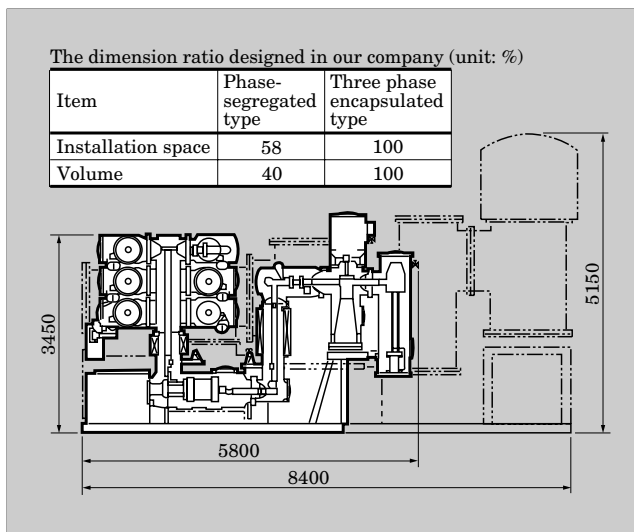


Fig.4 The sectional view of a GIS and the applied major technology

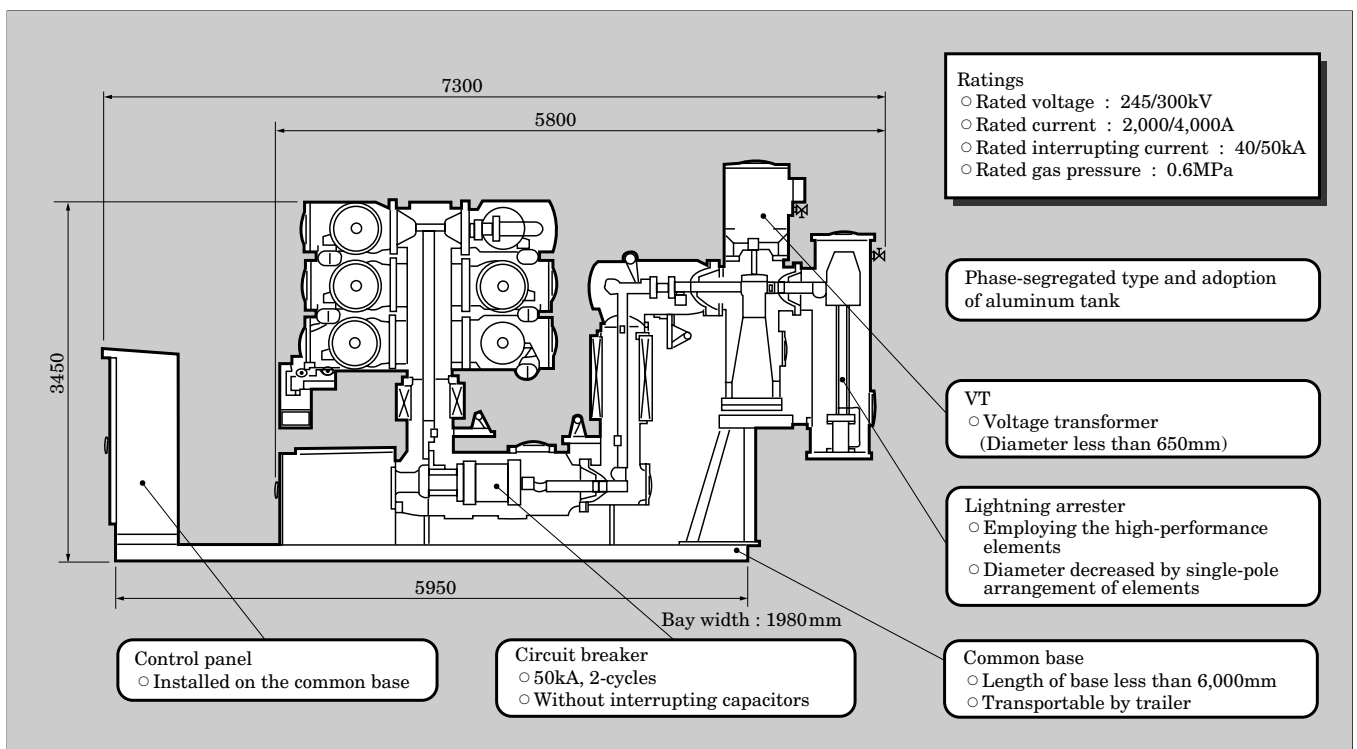
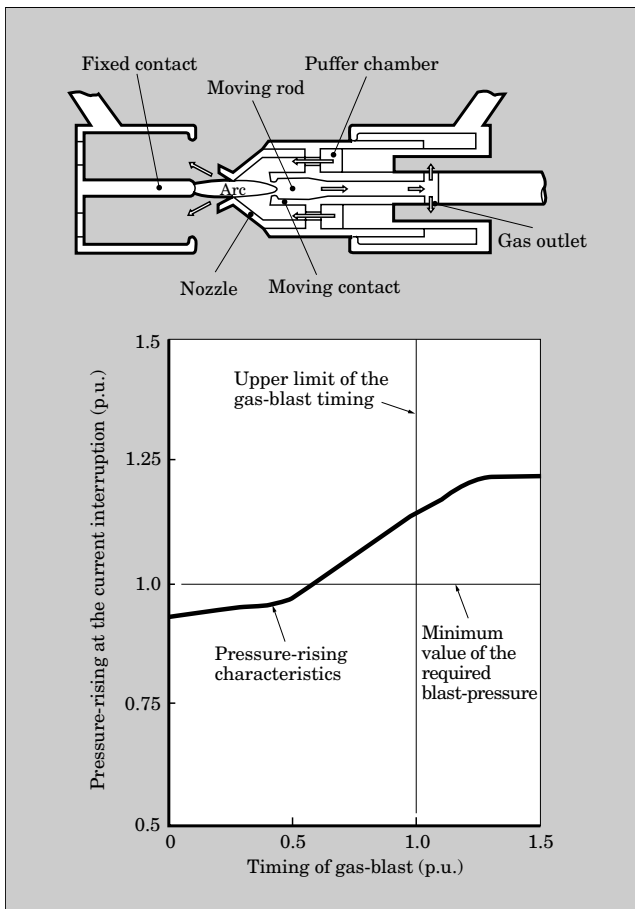


Fig.5 The pressure-rising after the beginning of gas-blast



(4) Easy on-site installation

The foundation work is simplified because of the small size and lightweight of the GIS. Because the GIS is fully assembled prior to transport, on-site connecting work is limited to the connection of busbars and cables. Therefore, the on-site working period can be shortened by 50%. Furthermore, since the control panel is mounted on a common base and then transported, it is unnecessary to connect control cables on-site.

(5) Easy troubleshooting

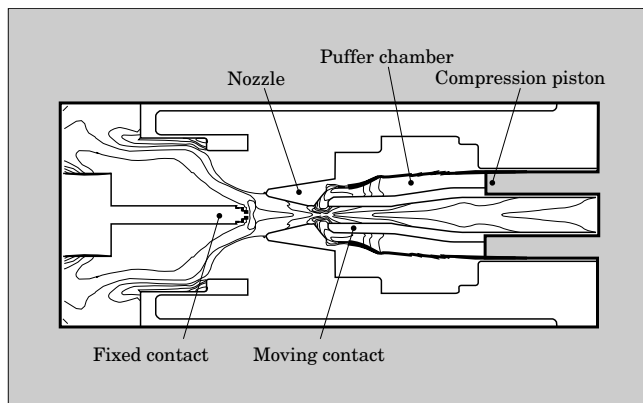
Because of the phase-segregated type construction, the areas of possible malfunction are limited. The weight of parts, such as the busbar, are light, and may be replaced easily without the need for large cranes.

5. Construction

5.1 Total construction

A cross-sectional view of a typical unit and the major technology applications are shown in Fig.4. Because the circuit breaker is located at the lowest position horizontally, total height is reduced and consequently, the fully assembled GIS (including the control panel) can be transported at one time. All of the tanks are made of aluminum castings. These aluminum casting tanks are not only beneficial to

Fig.6 Analysis of the gas density at the moment of 50kA-short current interruption



decreasing the weight, but are also well suited for machining and economical because they do not require welding. The pitch between phases is 650mm, the bay width is 1,980mm and the total weight is approximately 12 tons. Details of each apparatus are described below.

5.2 Circuit breaker

A new type of interrupting chamber has been developed that utilizes effectively the arc-energy generated during the current breaking to raise the interrupting gas pressure. Consequently, the diameter of circuit breaker tank was decreased to 70% compared to our conventional tank, contributing to the minimization of the new GIS. For the driving mechanism of the circuit breaker, a small, powerful, highly reliable hydraulic operating mechanism was utilized, and has yielded good operating results.

5.3 Isolators and earthing switches

To obtain stable operating performance, all of the remotely operated isolators and earthing switches are driven by motor-spring driving mechanisms. A thermal puffer type arc quenching system that efficiently utilized arc-energy is used with the earthing switches to break induced line current.

5.4 Lightning arrester

For the lightning arrester in the GIS, a high performance zinc-oxide device developed by Fuji Electric Co from a mixture of rare earth elements was used. Consequently, the single-pole arrangement of the device could be adapted even for UHV applications and a remarkably smaller size was realized.

5.5 Voltage transformer (VT)

The shape of the high voltage electrode was determined by means of electric field analysis to minimize the tank diameter. The construction was simplified to create VTs that can be arranged linearly with a 650mm pitch between phases.

Fig.7 An example of the 3-D field-analysis for the connection of the conductors between main circuit and circuit breaker

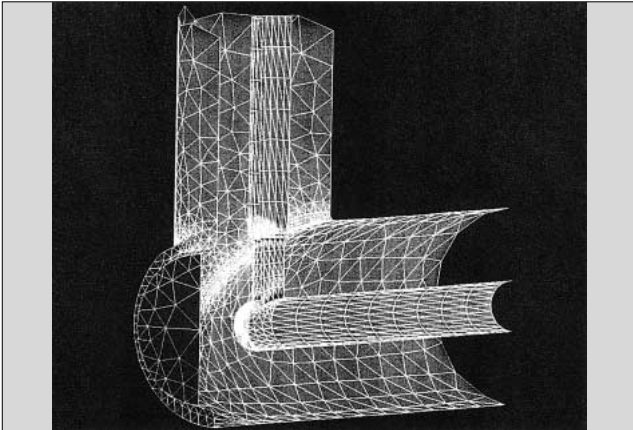


Fig.8 The state of earthquake-proof test

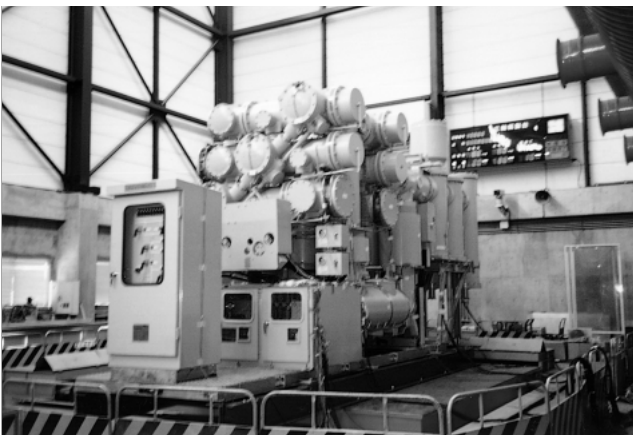


Fig.9 The state of transportation test



### 5.6 Current transformer (CT)

It was decided that the current transformer would be installed outside of the tank to utilize the characteristics of phase-segregated construction. Consequently, a CT primary current injection test can easily be performed by flowing the test current through the tank. For the purpose of CT testing, terminals for the

Fig.10 The state of freeze test

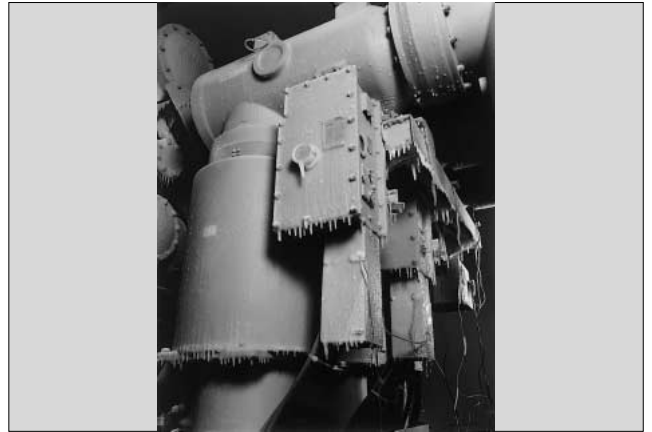


Fig.11 The state of long-term energizing test



test current are mounted on the tank.

## 6. Main Analysis Technologies

The main analysis technologies used to minimize elements of the GIS are listed below.

### 6.1 Interrupting pressure rise analysis

In the conventional circuit breaker, capacitors were installed in parallel between the main contacts in order to interrupt the large current easily. The capacitors function to mitigate the rate of rise of transient recovery voltage. However, a goal of this new GIS was to achieve interruption without the use of parallel capacitors. To achieve this goal, we improved the interrupting chamber so that the arc energy generated during the interruption contributes to raising the interrupting gas pressure, and blasting begins at the optimum point of interruption. Figure 5 indicates the results of the analysis.

### 6.2 Gas flow analysis

Since the hot gas generated by large current interruption is blasted out instantaneously into a

metal tank at ground potential, we improved the shape of nozzle and contacts and controlled the blowing direction of the hot gas so that the insulation ability would not decrease. An example analysis of the gas density distribution is shown in Fig. 6.

### 6.3 Electric field analysis

To analyze the electric field of complex parts such as the bent part of a conductor or the potential sharing on an arrester element with consideration of the back-side of conductors, three-dimensional electric field analysis by the surface-electric-charge method was applied. Figure 7 shows an example of the three-dimensional electric field analysis for the connecting part between a conductor of the main circuit and a circuit breaker.

## 7. Special Tests

The following special tests were implemented to verify the practical capacity of the GIS device. Sufficient capacity was fully verified.

### 7.1 Seismic tests

3m/s<sup>2</sup> 3-cycle vibration tests on resonant frequency were performed with a tri-axial vibrator and a safety factor of above 2 was verified. Additional seismic tests were performed using the “El-centro” wave, “Hachinohe” wave and “Kobe” wave, and the GIS was verified to be sufficient for earthquake-proof. The seismic testing is shown in Fig. 8.

### 7.2 Transportation test

The GIS was carried on a low-platform trailer, and tested with a rough road traveling test, a sudden start and stop test, and a test that ran over a square piece of timber. It was verified that there were no problems in any of these tests. The transportation test is shown in Fig. 9.

### 7.3 Heat cycle and freeze tests

With the GIS fully assembled, a heat cycle test between -35°C and +55°C and a freeze test were performed. It was verified that all of the equipment or devices operate normally under these severe conditions. The freeze test is shown in Fig. 10.

### 7.4 Long-time energizing test

A long-time energizing test was performed on an outdoor GIS for an interval of 8-months under the conditions of 200kV to earth and 4,000A. During the tests, each piece of equipment was operated intermittently, normal operation was verified, and there were no unusual states such as partial discharge or partial overheating. The long time energizing test is shown in Fig. 11.

## 8. Conclusion

A summary of the 300kV phase-segregated GIS (model: SDA530) has been presented. Fuji Electric will continue its efforts to minimize, and improve the quality and economy of the GIS.





# New Compact Gas-Insulated Switchgear

Takashi Fuji  
Teruo Ika  
Akira Nakamura

## 1. Introduction

The gas-insulated switchgear (GIS) has many advantages such as reduced size, high reliability, and laborsaving maintenance. Consequently, GIS applications have expanded both in domestic and foreign markets over the past decade.

Further, the trend toward reduced costs, especially the request for lower personnel expenses, is also affecting substation equipment. Reduced construction time, simplified transportation and installation work, and minimized installation space have been strongly requested.

In response to these requests, GIS has been eagerly developed with the goals of downsizing, lighter weight and improved maintenance. The development of the 72.5kV class GIS, which has the largest number of bays, is especially remarkable.

This paper describes details of Fuji Electric's newly developed, compact size GIS.

This development aims to decrease the size and improve the cost performance of the total substation through the elimination of dead space and consideration of maintenance ease, in addition to the minimization of equipment.

## 2. Ratings and Specifications of the New Compact GIS

The main ratings and specifications of the newly developed compact GIS are indicated in Table 1.

The outer view of a new compact GIS (cable feeder bay) is shown in Fig. 1, and the inner construction of the GIS is shown in Fig. 2.

## 3. Special Features of the New Compact GIS

### 3.1 Development concept

During development, we realized many new challenges, some of which applied new technologies, based on our history of shipping many 72.5kV GIS. These concepts are as follows.

#### (1) Expanded range of equipment-integration

By integrating equipment on the line-cable connec-

tion unit [isolator (DS), earthing switch (ES), lightning arrester (LA), voltage transformer (VT), etc.], the present 3-tanks should be decreased to 1-tank.

However, the busbar unit and circuit breaker (CB) unit shall remain with the same construction as in the present integration.

Table 1 Ratings and specifications

Type designation		SDH208
Rated voltage (kV)		72.5
Withstand voltage	AC (kV)	140
	LIWV (kV)	350
Rated normal current (A)		800, 1,200, 2,000, 3,000
Rated short-time withstand current (kA)		20, 25, 31.5
Rated SF <sub>6</sub> gas pressure (MPa)		0.5
CB	Rated voltage (kV)	72.5
	Rated interrupting current (kA)	20, 25, 31.5
	Rated interrupting time (cycle)	3
	Operating mechanism	Motor-spring
DS	Rated voltage (kV)	72.5
	Operating mechanism	Motor, motor-spring
ES	Rated voltage (kV)	72.5
	Operating mechanism	Motor-spring, manual
LA	Type	ZnO
	Rated voltage (kV)	84
	Nominal discharge current (kA)	10
	Switching surge duty capa. (μF)	25
VT	Type	Gas-insulated winding type
	Rated primary voltage (kV)	66
	Rated secondary voltage (V)	110
	Rated tertiary voltage (V)	110/3
	Rated burden (sec./tert.) (VA)	3 × 500/3 × 200
Accuracy (sec./tert.) (class)	1P/3G	
CT	Type	Gas-insulated, cable mount
	Rated primary current (A)	According to customer's spec.
	Rated burden (VA)	10, 40
	Accuracy (class)	1P

Fig.1 Outline of newly developed GIS (cable-feeder bay)

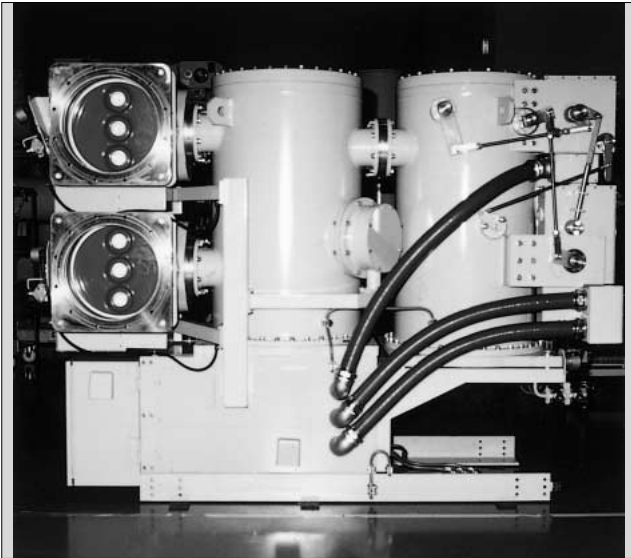
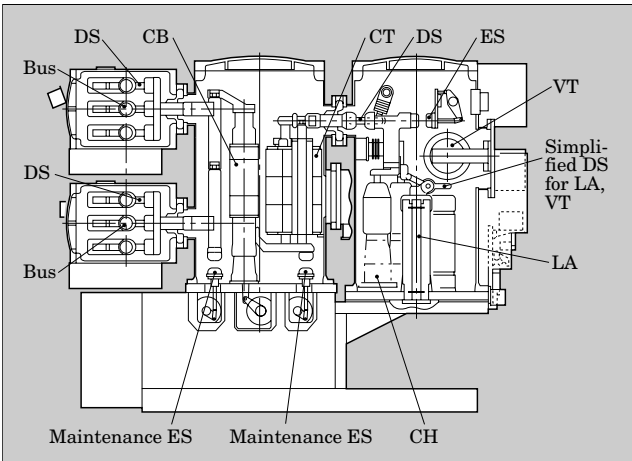


Fig.2 Sectional view of newly developed GIS



(2) Application of aluminum casting for the busbar tank

The use of aluminum casting for the busbar tank is expected to result in lighter mass and suppress the temperature rise.

(3) Structure that allows maintenance from front and rear

Operating mechanisms and monitoring devices that require maintenance are arranged at the front and rear of the GIS. Maintenance and inspection between bays is unnecessary.

(4) Low profile

Since the total height of the GIS is designed to be low, inspection scaffolding can be omitted. Further, since the fully assembled transportation of two or more bays is possible under certain circumstances, the onsite construction time can be shortened and productivity improved.

Fig.3 Principle of arc-quenching

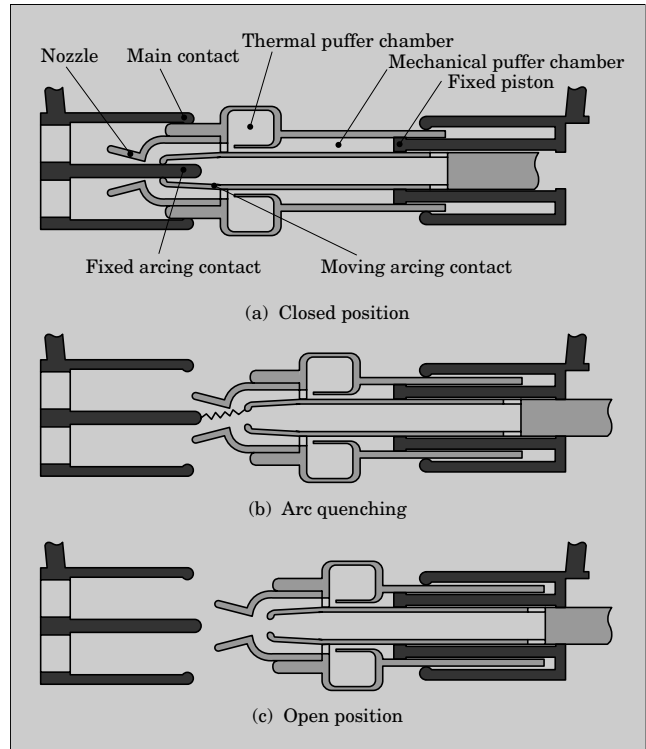


Fig.4 3-D model for earthquake analysis

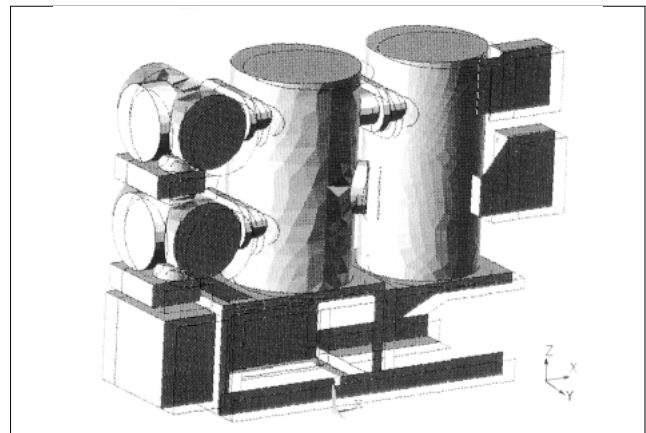


Fig.5 3-D model for electric field analysis (cable sealing end, lightning arrester)



### 3.2 Application of new technology

The following new technologies have been utilized in the development of the GIS.

- (1) Application of a mechanical and thermal puffer to the CB-interrupting unit, and application of a motor charged spring-type operating mechanism

This interrupting method has been widely used in the dead tank type SF<sub>6</sub> gas circuit breaker (GCB) and in the cubicle type GIS, but this is the first application to the GIS. The interrupting chamber of this method has two main mechanisms, one is the thermal puffer (self-arc-extinguishing) which increases the blast-gas pressure utilizing the thermal energy generated by the arc itself, and the other is the mechanical puffer in which the blast-gas pressure is generated mainly by mechanical compression and is useful for small current interruption.

By utilizing the thermal puffer, the operating energy could be decreased to less than 50% that of the conventional type of mechanical puffer. To help decrease the operating energy, a low-power motor-charged spring type operating mechanism was applied as a standard part.

- (2) Application of high-performance lightning arrester

By decreasing the thickness and increasing the

withstand voltage of the ZnO element, the height of the arrester unit could be shortened and its weight made lighter. Further, the residual voltage could be decreased.

By downsizing the arrester unit, the line-side

Fig.7 Comparison of the overload current carrying capability

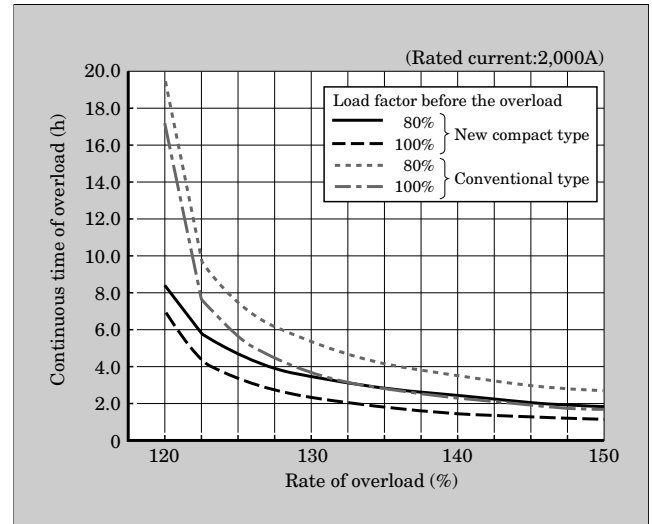


Fig.8 Transportation of full assembled GIS

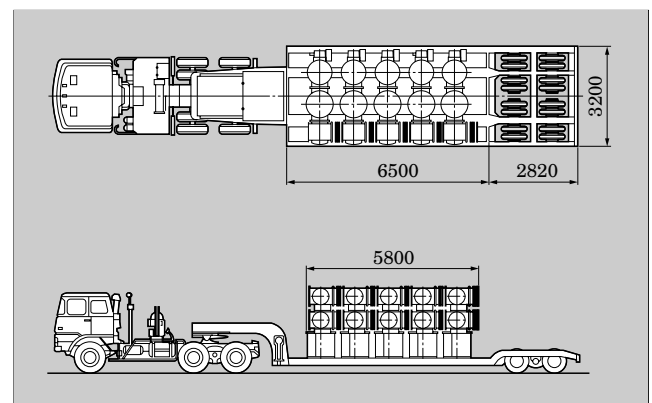
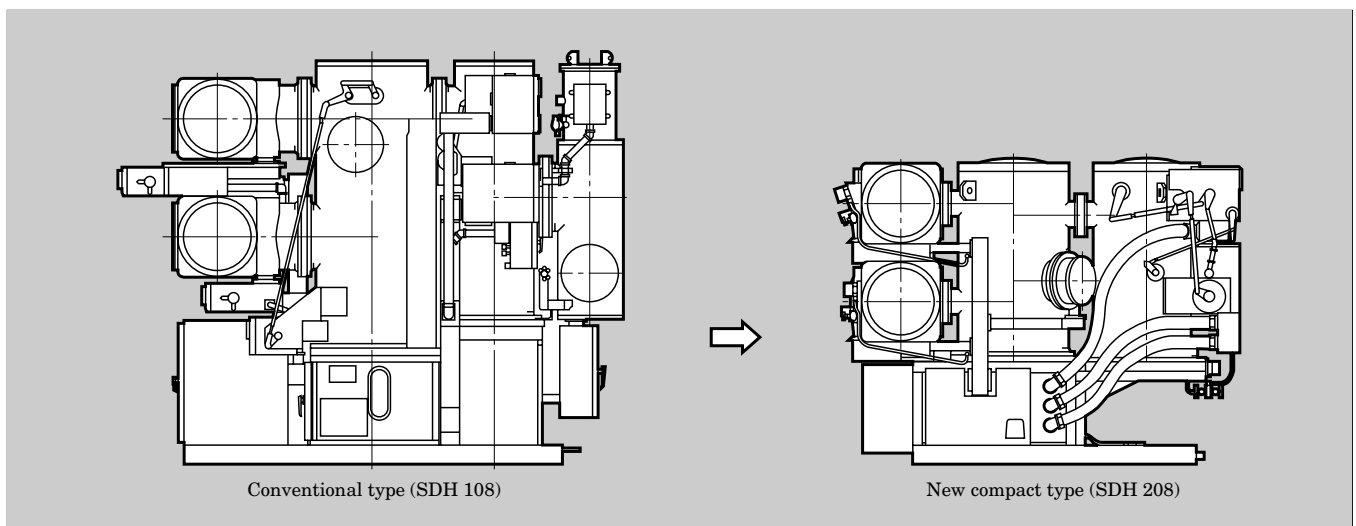


Table 2 The comparison between conventional type and new type

Item	Type	Conventional type	New compact type
Height	(mm)	3,100	2,300
Depth	(mm)	3,500	2,700
Bay width	(mm)	1,500	1,100
Mass	(%)	100	68
Installation space	(%)	100	57
Volume	(%)	100	42
Number of parts	(%)	100	70

Fig.6 Outline comparison of each type GIS



equipment could be integrated, the insulation coordination improved, and the LIWV decreased.

All of the newly designed parts, including the application of new technologies, were evaluated by 3D-electric field analysis and mechanical stress analysis. In addition, the specified and practical tests have been verified with an actual prototype GIS.

As an example analysis, the 3D-model for earthquake analysis is shown in Fig. 4 and the 3-D model for electric field analysis is shown in Fig. 5.

### 3.3 Comparison with conventional GIS

The new compact GIS, developed based on new concepts and new technologies, is compared to the conventional GIS and the results are shown in Table 2 and Fig. 6. By decreasing the bay width to 1,100mm, the total volume was decreased to 42% of that of the conventional GIS.

This fact can contribute, especially in the case of indoor substations, directly to decrease building dimensions and reduce costs. On the other hand, the increased rate of equipment integration and downsizing of the tank could lower the rated tolerance for temperature rise and the overload current carrying capability could become less than that of the conventional GIS. The overload current carrying capability at the rated current of 2,000A is shown in Fig. 7.

In the past, each GIS bay was transported on a

separate low-platform trailer. Now, the new compact GIS can be transported two bays at a time on a 10-ton truck, or completely assembled five bays at a time on a low-platform trailer (Fig. 8). These conditions are expected to decrease the onsite installation time.

To guarantee reliability, the following items in the GIS maintain their conventional construction.

- (1) SF<sub>6</sub> gas-insulated current transformer (CT)
- (2) Straight line arrangement of conductors in a gas-tight support insulator
- (3) Straight line movement of DS/ES contacts
- (4) Application of a motor charged spring-type operating mechanism to the DS/ES with current switching capacity

## 4. Conclusion

A summary of the new compact GIS has been presented. This GIS has been tested with the model test and special tests according to the related standards of each piece of equipment; good results were obtained, and consequently the verification of performance and functions of this GIS is complete.

In the future, we plan to make this new GIS maintenance-free, improve trouble shooting, and increase reliability furthermore. We sincerely hope that the customer would provide us with much of advice and encouragement in the future.



# Recent Power Transformer Technology

Kenji Ookubo  
Masaaki Kousaka  
Kenji Ikeda

## 1. Introduction

Power transformers are essential components of substation equipment for the efficient and stable operation of electric power systems. There is demand for transformers with lower price and higher reliability. In addition, depending upon the onsite conditions, such as narrow roads, mountainous areas or highly congested urban areas, harmony with the surrounding environment is required throughout shipping, installation and operation. Contribution to the global environment throughout the transformer life cycle is also required.

As topics of recent interest, we have been promoting the application of the technology of UHV level equipment to general power transformers, and focusing on the Hanshin-Awaji great earthquake disaster, the reinvestigation of disaster prevention and safety.

In response to diverse requirements, Fuji Electric has always developed and applied new and reliable technology. This paper describes recent features of power transformer technology.

## 2. Oil-Immersed Large Power Transformers

### 2.1 Structuring technology for the core and windings

The core and windings are important components determining basic performance and reliability that should always be maintained and improved. However, the core and windings are also a source of energy loss, causing problems in the energy environment. To conserve resources, it is necessary to downsize these components and lighten the materials used. Moreover, these components occupy a large percentage of the cost. It is also necessary to develop fast- and easy-to-make structures because Japanese labor, at present, is among the most expensive in the world. Fuji Electric has been promoting technological development with total evaluation and measures to overcome these contradictory problems, and the coordinated and harmonized marketing of products.

#### 2.1.1 The core

We have utilized high-grade grain-oriented silicon-steel sheets in the core, selecting material with thin

sheets, coating-processed sheets, or high magnetic flux density (B8), corresponding to the requirements for low no-load loss or low sound level.

To reduce the man-hours required for assembly and work lead-time, we have standardized the types of materials and components used in the core. The manufacturing process automates a series of operations; the automatic press line cooperates with the Fuji Electric's original automatic core stacking facility to make the cutting of silicon steel sheets and stacking work of the lower yoke and legs in a sequence. The facility stacks the cut core sheets on the core erection equipment and stands them upright as a core. Glass-fiber bands are commonly used to bind the core into a single unit. This process helps stabilize the performance quality of the core.

For three-phase large power transformers, if it is desirable to reduce the weight of the upper yoke for a transformer with rated power of 600MVA or more, or if there is a limitation in height for transportation, we utilize a five-legged core instead of a three-legged construction.

#### 2.1.2 The winding

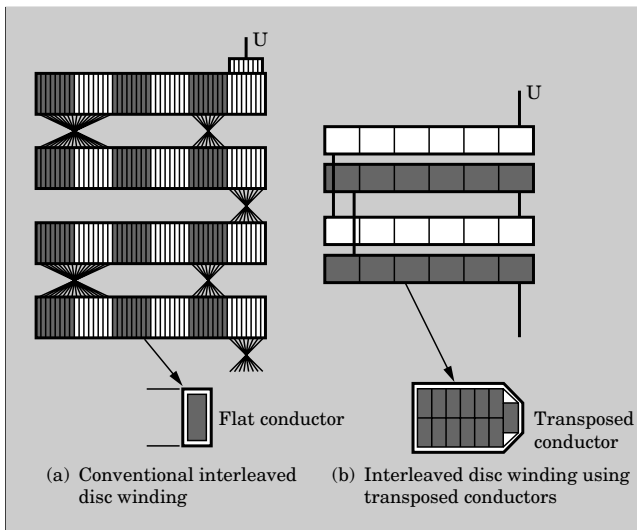
Fuji Electric has aggressively expanded the use of transposed conductors for windings. Transposed conductors make the continuous winding work reasonably easy and shorten the required man-hours and work lead-time, they are also useful to decrease the eddy current losses in the winding.

##### (1) Interleaved disc winding using the transposed conductors

Conventional high voltage windings use from two to ten or more flat conductors with normal or common insulation paper to construct the interleaved disc winding. In this case, a high series capacitance can be obtained from the capacitance between conductors that are repeatedly wound in the radial direction of the coil.

Interleaved disc winding using transposed conductors is introduced to increase series capacitance by creating a disc coil with one or two transposed conductors in such a way that the conductor of the first coil extends over to the third coil and then returns back to the second coil. In this manner, a high series capacitance can be obtained from the capacitance

Fig.1 Coil configuration of interleaved disc winding



between coils that are axially arranged. Figure 1 compares coil compositions and conductor connections of the interleaved windings.

The conventional continuous disc winding has been widely utilized in transformers, including extra-high-voltage class transformers, to increase the efficiency of winding manufacturing and decrease the eddy current losses in the winding. In addition, the aforementioned interleaved disc winding demonstrates excellent lightning impulse voltage withstand characteristics, and contributes to reduced equipment size when applied to the extra-high-voltage class. The winding work and insulation performance was verified using the actual-scale winding model shown in Fig. 2.

(2) Self-bonded transposed conductors

Short-circuit current flows into the winding when the system connected with the transformer is short-circuited, and then an electromechanical force is generated in the winding. Conductor strength must be improved so that the transformer can withstand this electromechanical force that increases with transformer rated power. The use of stiff material such as semi-hard copper increases the lead-time for winding work on the winding form.

The self-bonded transposed conductor consists of element wires enameled with heat-stiffened resin. After forming the winding, the element wires are heated to dry, and during this time they are integrated en bloc. This improves the strength of the conductors and the winding. After the winding is completed, direct current is supplied and the conductor is heated to securely integrate the element wires into a single unit and stiffen the winding itself.

2.2 Insulation technology

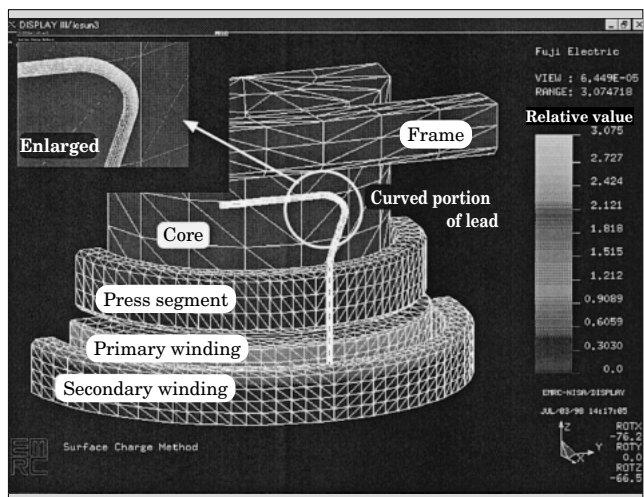
2.2.1 Review of insulation structure

The insulation of the oil-immersed transformer is basically a composite insulation structure consisting of insulation oil and oil-impregnated paper. Depending

Fig.2 Actual-scale model of interleaved disc winding using transposed conductors



Fig.3 Three-dimensional electric field analysis for terminal lead outlet



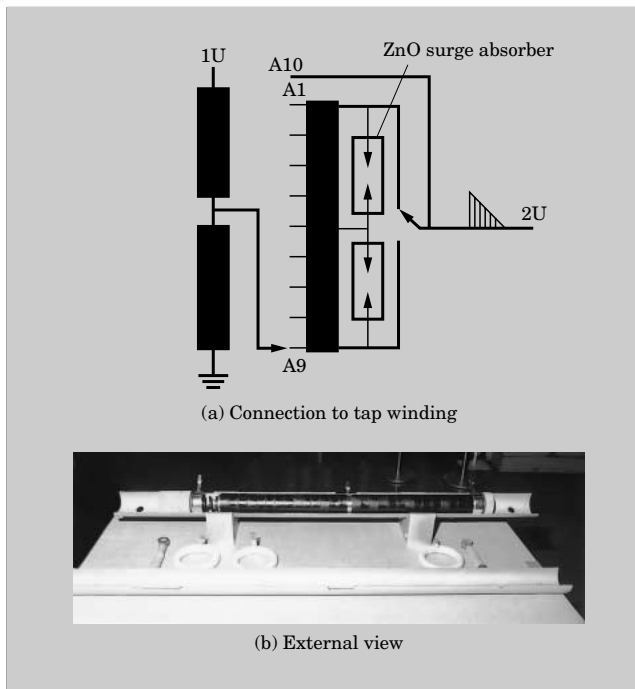
upon the shape of the conductor and its coating insulation, the oil may be separated into multiple layers by molded barriers.

Depending upon the insulation structure, analysis is performed using the finite element method (FEMT), finite difference method (FDMT) or the surface charge method, and work is performed to simplify and make efficient the structure while maintaining the reliability of the insulation.

Figure 3 shows an example of three-dimensional analysis by the surface charge method. This example analyzes the electric field distribution around the high-voltage lead conductor extracted from the upper part of a winding. The computational accuracy of conventional two dimensional electric field analysis is limited because the curved portion of the lead and the shape of



Fig.4 ZnO surge absorber



AM183541

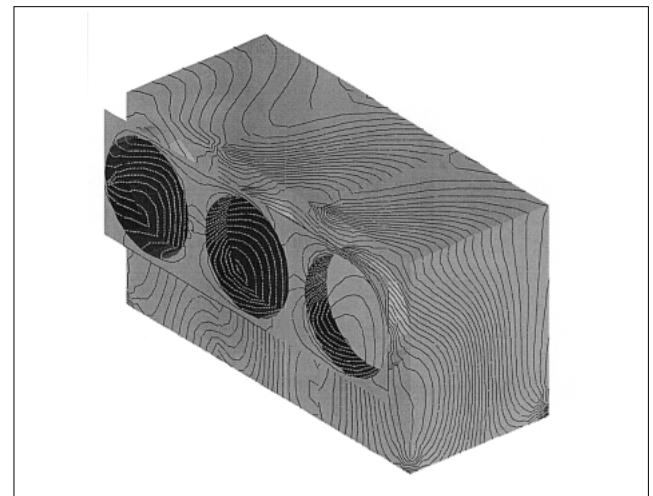
grounded peripheral parts are influenced by the electric field. However, it is possible to understand the electric field distribution in detail with such three-dimensional analyses and to find a reasonable insulation structure.

Moreover, to improve the reliability of the insulation structure, we have carefully observed the detailed mechanism at the start of partial discharge. We implement precise measures to control the withstand voltage tolerance, utilize insulating materials with low dielectric constants, and arrange the shield on the grounded side.

### 2.2.2 ZnO surge absorber

In an extra-high-voltage transformer, when the lightning impulse voltage impinges on the winding terminal, a voltage oscillation occurs within the winding and across the tap coils. This voltage oscillation occasionally becomes a problem depending upon the winding arrangement, connecting conditions, and the tap positions of the winding, and therefore, requires enlargement of the insulation distance or reinforcement of the insulation structure. To avoid this potential problem, we use a ZnO surge absorber with a nonlinear voltage characteristic connected to the corresponding winding part and to suppress excessive oscillatory voltage. Installing these elements in the transformer tank simplifies the associated insulation structure and makes the entire equipment more compact. Figure 4 shows the external view and the application example of the ZnO absorber. A long-term excessive voltage test has verified the reliability of the ZnO absorber with no deterioration.

Fig.5 Three-dimensional current distribution analysis of the connection box



## 2.3 Technology for reducing eddy-current and stray load losses

On the load losses of the transformer, it is possible to exactly calculate the resistance and eddy-current losses in the winding. However, the source of stray load loss cannot be determined since only the difference of measured load losses and the aforementioned calculated losses are obtained as collective values. At Fuji Electric, stray load loss is being closely studied to locate the source of the stray load loss, and to decrease the amount of loss.

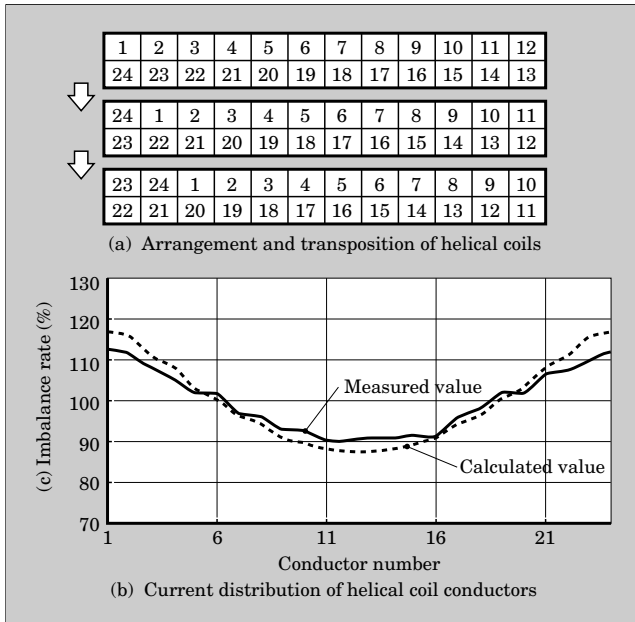
### 2.3.1 Three-dimensional magnetic field analysis

Because the amount of magnetic flux that overflows from the winding or is generated around the large current lead increases with the transformer rated power, the study of magnetic flux is indispensable in the evaluation of eddy currents, stray load loss of adjacent structures, and in the implementation of measures against local overheating.

To implement a reasonable design specific to the structures and the materials, Fuji Electric performs three-dimensional magnetic field analysis and precisely computes the current distribution in the structural paths, the eddy current distribution and the associated losses. In addition to the losses, we also evaluate the temperature distribution in the structures based on the above calculation results.

Figure 5 shows an analysis of the current distribution in the connection box, where large currents flow from the transformer primary side to phase-isolated buses connected with the generator in a power plant. This example shows that it is possible to construct a common connection box for all three phases instead of independent connection boxes for each phase as has been done in the past. This figure shows neither an abnormal current concentration nor cause for local overheating, as seen from the currents displayed as line bunch flows on the box.

Fig.6 Analysis and measurement of unbalanced currents between conductors with the helical coil windings



### 2.3.2 Measures against eddy-current and stray load losses in the winding

In windings that carry extremely large currents, we use many conductors connected parallel. The linkage of each conductor with the leakage flux slightly differs, and therefore, causes an imbalance in the currents among the parallel conductors and increases the load loss. This load loss adds to the eddy current loss that is usually calculated on the assumption of balanced currents. We can decrease the imbalance of these currents by selecting the optimal way of transposition of each conductor.

Fuji Electric has developed simulation software for these unbalanced currents to choose the best transposition method. Figure 6 shows an example of the current imbalance rate between conductors in helical windings.

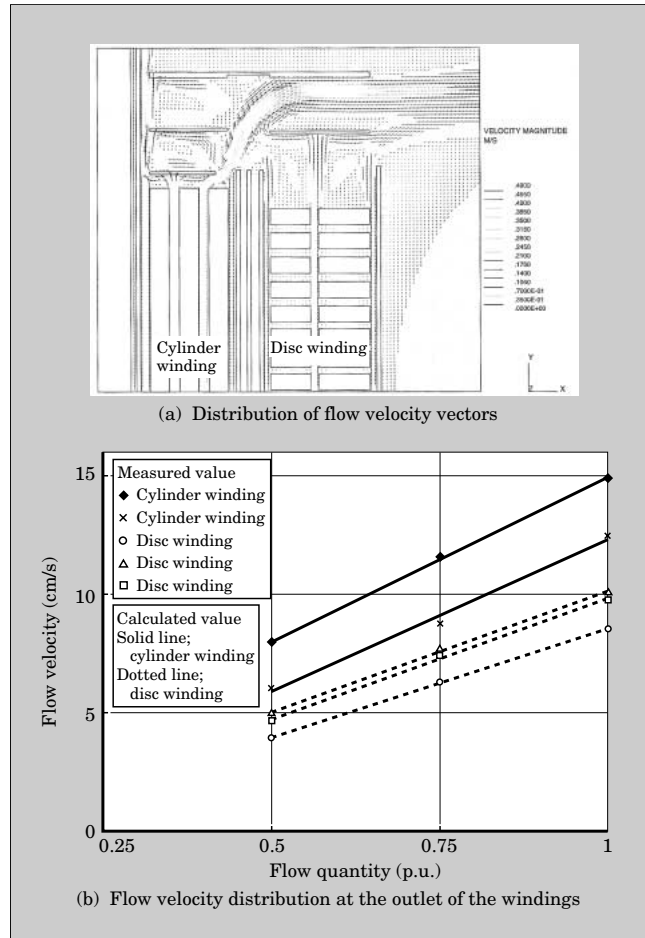
## 2.4 Cooling technology

### 2.4.1 Oil-flow velocity distribution inside and outside the winding

To optimize the cooling structure inside and outside the winding, it is necessary to understand the oil-flow distribution in detail.

For this purpose, we used a three-dimensional supersonic wave Doppler flow velocity meter. This meter is capable of detecting echoes of supersonic wave pulses that are reflected from a tracer particle moving in oil, and measures the three-dimensional instantaneous flow velocity. A gas bubble was inserted into the oil as the target tracer. On the other hand, we used general-purpose heated fluid analysis software (finite volume method) to obtain the oil-flow velocity. The principal equation is the law of conservation of mass

Fig.7 Oil-flow velocity distribution inside and outside the windings



and momentum. The software performs a steady state analysis using a turbulent flow model.

Figure 7 shows an example of the analysis and the measurement of the oil-flow velocity distribution for the actual-scale model. The agreement of these results is comparatively good.

Because this technique can confirm whether the oil-flow velocity distribution meets the design objective, we can accumulate data and then apply it to practical designs.

### 2.4.2 Zigzag oil-flow

In directed oil-flow type transformers, we mainly use the zigzag oil-flow method instead of the conventional duct flow method. The zigzag oil-flow method improves heat transfer from the winding to oil, makes a balanced distribution of the winding temperature rise, and decreases the highest temperature of the transformer. As results, this method decreases the size of the cooling equipment and improves the reliability. Comparison of the modeled analysis and actual measurements using an actual-scale model has verified good agreement of the temperature distribution, and made it feasible to choose the best oil-passage structure, including the method of arranging the curving plates.

Fig.8 Shipping of the transformer with the steel plate dampers mounted



## 2.5 Noise reduction technology

The sound level of a transformer, i.e. the noise, is now a regulatory problem closely related to the city life environment in urban areas and the home life environment in residential areas. Low noise specifications for power transformers are universally spread throughout the domestic marketplace.

To decrease the transformer noise, it is important to use core sheets with small magnetostriction, to improve the corner jointing of core sheets, and to optimize the soundproofing equipment, including that of the coolers. With consideration of the noise specifications, Fuji Electric always tries to apply optimal anti-noise measures. We also try to devise an optimal shipping form as well as to simplify onsite construction work as much as possible.

On the other hand, to clearly find the relation between vibration and transformer noise, we are investigating with basic numerical analysis.

### 2.5.1 Step-lap jointing of the core corner

Changing the jointing method of the core corner sheets from the conventional bat-lap joint to the step-lap joint decreases the transformer noise approximately 4 to 6 dB(A). The exciting current and no-load loss can also be decreased. Fuji Electric utilizes the step-lap joint as a standard for low noise specifications.

### 2.5.2 Steel sheet dampers

Steel sheet dampers sandwich the resin between two thin steel plates and attenuate the vibration effected by the shear deformation of the resin. Steel sheet dampers have been used since the 1970's and Fuji Electric recently attained a sound level of 60 dB(A) for a three-phase 450MVA transformer. Figure 8 shows an application example for the transformer.

### 2.5.3 Sound emission analysis

The boundary element method is applied to sound emission analysis in which the given vibration distribution of the transformer surface is used to compute the sound level distribution on a plane separated some distance from the transformer. By selecting a boundary surface through which the sound propagates, this method solves the wave propagation equations for this surface in terms of a boundary integration formula. We used laser light to measure the vibration distribution on the surface of a three-phase model core, and calculated the sound level distribution [dB(A)] in a plane 30cm from the core. Figure 9 compares example data for typical high harmonics of the vibration and noise.

## 3. SF<sub>6</sub> Gas-Immersed Transformer

As nonflammable substation equipment, SF<sub>6</sub> gas-immersed transformers attracted attention when the manufacture of transformers containing PCB (poly chloro biphenyl) synthetic oil was prohibited due to environmental pollution problems. Since the latter half of the 1980's, SF<sub>6</sub> gas-immersed transformers have been widely used to improve disaster prevention, safety, and the environmental harmony of electric equipment. Recently, this trend has been accelerated especially in Japan and China, including Taiwan and Hong Kong. In Japan, the scope of application currently ranges from small distribution transformers of the 6kV class to extra-high-voltage large power transformers.

SF<sub>6</sub> gas-immersed transformers are best suited for the various performance requirements of urban substations. Because a conservator is unnecessary, the ceiling height can be reduced in rooms where this transformer is installed. This contributes to reduced building construction costs.

### 3.1 Details of development

Fuji Electric has extended the product series of the SF<sub>6</sub> gas-immersed transformers as follows.

- (1) For the 6kV class, products from 50 to 2,000kVA have been standardized as a series.
- (2) For the 22 to 77kV class, products from 3,000 to 15,000kVA, for which most demand is expected, have evolved into a new series, the ALFOS  $\Sigma$ , with a new structure that uses windings of aluminum foil sheets.
- (3) For high-voltage and the large power rated class, Fuji Electric has already delivered 3-phase 154kV/25MVA and 3-phase 110kV/40MVA units.

### 3.2 Prototype transformer for 66kV/60MVA

Advancing toward the production and marketing of large power rated 3-phase 66kV/60MVA gas-immersed transformers with SF<sub>6</sub> gas-directed forced-water cooling for intermediate substations, a prototype for one

Fig.9 Analysis and measurement of vibration and noise distribution for the three-phase core model

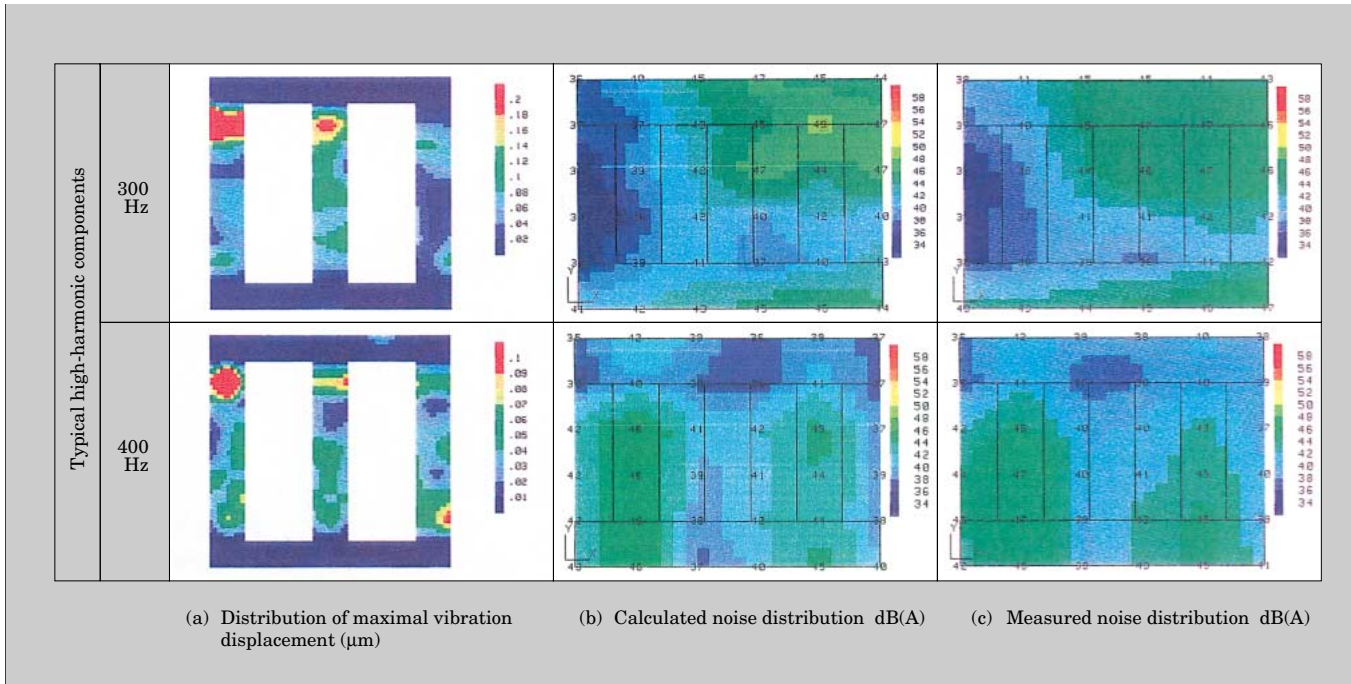
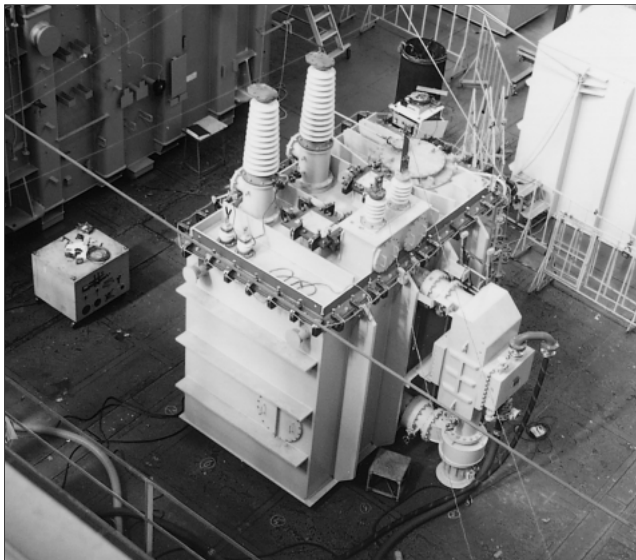


Fig.10 SF<sub>6</sub> gas-immersed prototype transformer being tested for reliability (Single-phase, 60/3MVA)



AM183483

phase of this transformer was manufactured for trial and verification purposes.

Figure 10 shows the transformer being tested, and Table 1 lists the specifications of the prototype transformer.

Before designing the prototype, Fuji Electric studied the component technology as part of the developmental work for this transformer, confirmed its performance using three-dimensional electric field analysis, gas flow analysis, model experiments, etc., and established insulation and cooling design technology as well as measures against short-circuit electromechanical

Table 1 Specifications of the 66kV 60MVA SF<sub>6</sub> gas-immersed transformer prototype

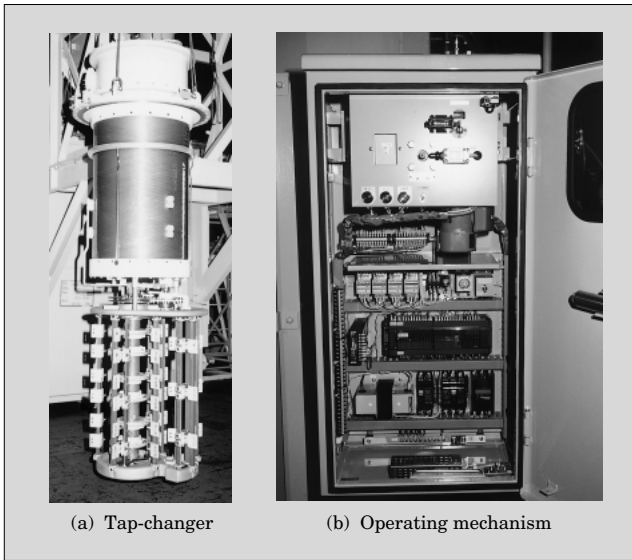
Standard	JEC-2200-1995
Cooling method	Gas-directed and forced-water (GDWF)
Insulation system	E
Maximum winding temperature rise	49K
Number of phases	Single
Frequency	50Hz
Rated power	60/3MVA
Rated voltage	Primary : $66/\sqrt{3} \pm 6/\sqrt{3}$ kV (17 taps) Secondary : $22/\sqrt{3}$ kV
Rating	Continuous
Short-circuit impedance	16%
Withstand test voltage	Primary : LI 350kV AC 140kV Secondary : LI 150kV AC 50kV
SF <sub>6</sub> gas pressure	0.13MPa (gauge pressure at 20°C)

forces.

The insulation system of the transformer is class E. However, the primary winding uses Nomex-insulated electric wires (class H) to provide sufficient tolerance for the short-time overload capacity. The primary winding uses a mixed interleaved disc winding for improved insulation reliability against lightning impulse voltage. The secondary winding uses heat-resistant self-bonded transposed conductors for improved mechanical strength. Consequently, a unit could be assembled with smaller size and lighter weight than before.

This prototype equipment passed all the tests prescribed in the JEC Transformer Standard and

Fig.11 Vacuum switch type on-load tap-changer



AM167807 / AM152856

demonstrated sufficient quality to enter production. The high degree of correspondence between the component technology and the performance of the prototype equipment confirmed that larger equipment could be manufactured without problems.

### 3.3 Vacuum switch type on-load tap-changer

The aforementioned SF<sub>6</sub> gas-immersed transformer is equipped with a 600A on-load tap-changer system consisting of two resistors and four vacuum switches with an electronically controlled operating mechanism shown in Fig. 11. The two models of 400A and 600A

tap-changers can now be used with SF<sub>6</sub> gas-immersed transformers.

Advantages of this on-load tap-changer are listed below.

- (1) The current is switched with vacuum switches, which are installed in a SF<sub>6</sub> gas-immersed chamber separate from the transformer tank.
- (2) The switching mechanism of a two-resistor and four-vacuum-switch system assures high reliability. The vacuum switches are secured by a cassette structure that facilitates the inspection work.
- (3) Since the roller contacts are used to connect the tap selector with the winding taps in the transformer tank, harmful metallic wear powders do not peel off.
- (4) The operating mechanism has achieved high performance with electronic and digital control. This contactless method assures improved reliability and maintainability.

## 4. Conclusion

Fuji Electric will continue to aggressively introduce new materials, to develop components and processing methods to promote resource conservation and recycling, to further develop advanced technology in response to the requirements of society, and to implement useful proposals for reducing the total life-cycle cost, that is, to help optimize the investment of the customer side. In addition, we will also continue development of transformer peripherals, for example, active noise control.



# Fuji Advanced Transformer Reassembled at Site (FATRAS)

Makoto Yamaguchi  
Kazuaki Yokouchi  
Nobuo Noguchi

## 1. Introduction

The steady growth of power demand in recent years has increased demand for transformers with higher voltage and larger rated power, which inevitably enlarges their size and mass. Environmental restrictions are becoming severer year by year. When installing transformers in hydropower stations located in mountainous areas or substations located in urban and suburban areas, transportation costs will increase particularly when widening roads, reinforcing bridges, removing obstacles, etc. are required. To minimize the total transformer costs, including equipment, transportation and onsite installation costs, Fuji Electric has developed and implemented an onsite reassembled type transformer (FATRAS: Fuji Advanced Transformer Reassembled at Site), which allows use of a general-purpose low-platform trailer for inland transportation.

## 2. Features of FATRAS

In general, after a transformer is completely assembled and tested at the factory, only external components and accessories are disassembled for transporting. When there are severe restrictions on the transportation, such as if the transformer is located on a mountainous area, a special three-phase construction type or a bank of three single-phase units are utilized and the transformer is transported with special freight cars (Schnabel or garter wagons) for inland transportation.

FATRAS makes it possible to use general-purpose low-platform trailers without adversely affecting environmental shipping restrictions.

Figure 1 shows a conceptual workflow of FATRAS. At the factory, the transformer is completely assembled as a normal three-phase unit and tested to verify its performance and quality. Then, some main components, such as cores, windings and tanks, are disassembled so that a general-purpose low-platform trailer may be used. The number of the components disassembled is reduced as much as possible for easier onsite reassembling. In a temporary dust-proof air-conditioned building at the site, the core and windings

are reassembled and the divided tanks are combined. After the tank is completed, external parts, such as bushings, coolers, etc. are mounted. After drying the windings and insulation, the transformer is filled with oil and then tested to reconfirm that its performance and quality are equivalent to those before disassembling at the factory.

Table 1 shows a comparison of the 500kV 1,000MVA layout for FATRAS and for conventional three single-phase units.

## 3. Construction of FATRAS

### 3.1 Core

As shown in Fig. 2, a five-legged three-phase core construction is utilized for FATRAS. The core construction is such that, after removing of the upper yokes and windings, it can be split into four parts at each center of the main legs. For transportation, the lower core part is held in place by custom jigs and placed in the transportation tank to prevent deformation of the core or changes in the joint-gaps during transportation. Onsite assembling does not require erecting the cores as they are shipped upright, and only requires adjusting and fitting the split core parts together and mounting the upper yokes.

### 3.2 Winding

To simplify disassembling and reassembling, the HV, LV and tap windings are constructed in a single unit for each phase. The winding assembly is packaged in a high-polymer film to protect from moisture and dust during disassembling at the factory, shipping, and reassembling at the site. Existing openings of the package are bonded with tape for airtight sealing and easy handling.

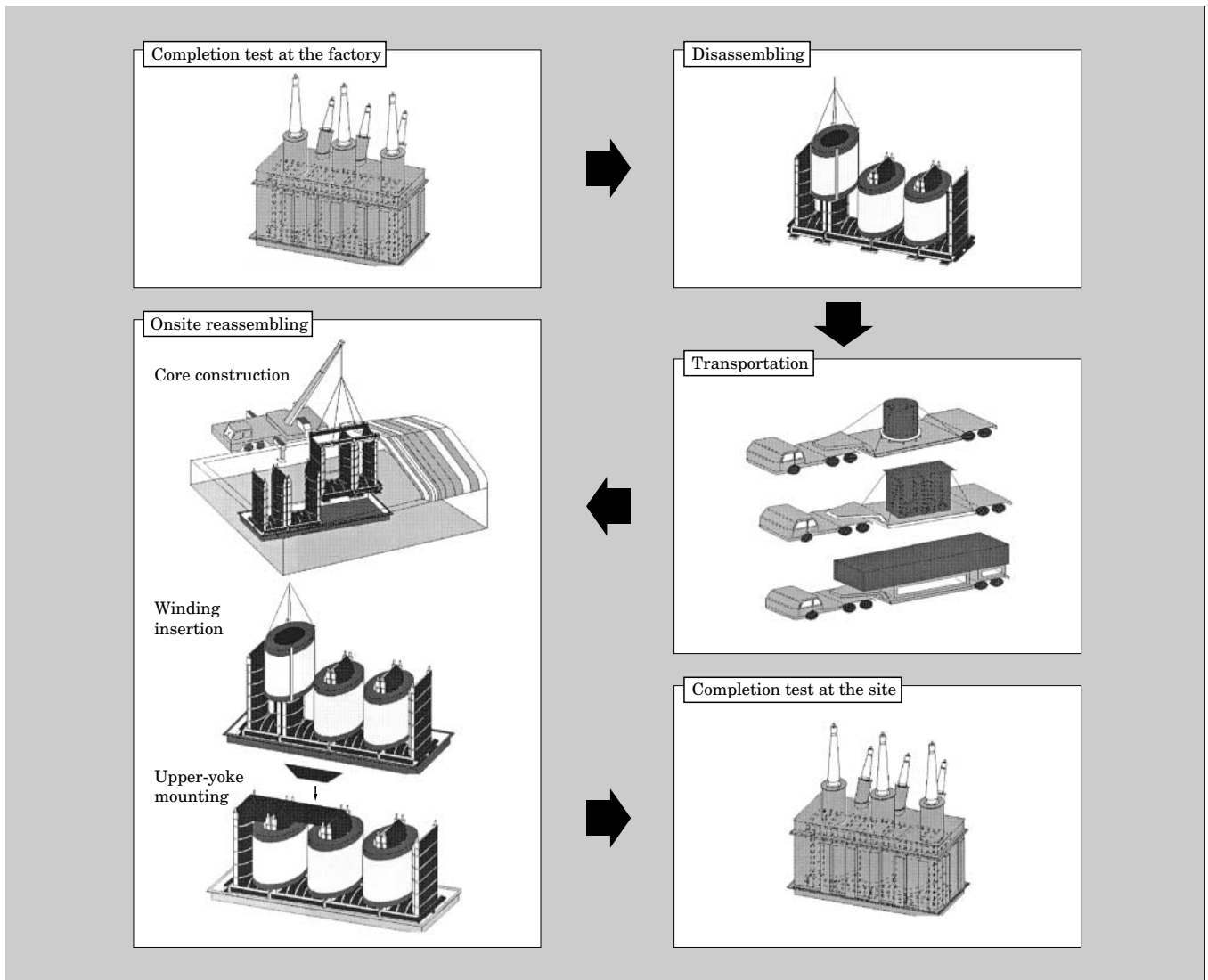
Figure 3 shows a photograph of the packaged winding assembly.

### 3.3 Tank

The tank is divided structurally into three parts, i.e., upper, middle and lower parts, in consideration of the transportation limits. The lower tank is used as the base for assembly of the core, and the middle tank



Fig.1 Overview of FATRAS



is used as a transportation tank for the yokes and tap leads. Figure 4 shows a conceptual view of the tank construction.

#### 4. Reliability Verification Tests

The core and windings of FATRAS are disassembled after testing at the factory, and then reassembled at the site. This procedure is very different from that of the conventional transformer. Therefore, the following tests specific to FATRAS were carried out to verify reliability for practical use.

##### 4.1 Core performance test

Two reduced-scale (1/5) models, a main-leg-split type (for FATRAS) and a conventional type, were made of a three-phase 250MVA five-legged transformer. The tested core characteristics, i.e. no-load loss, excitation current etc., were confirmed as substantially equivalent for both the conventional type core and the main-leg-split type. Figure 5 shows the five-legged

three-phase core model during testing.

##### 4.2 Core transportation test

After disassembling the upper yokes, a U-shaped core is fitted to transportation tank. Actual 250MVA core models were transported for 400km and then reassembled to compare the core performance both before and after the transportation. No gap or damage was found on any section of the core. In addition, the electric performance tests yielded good results. Figure 6 shows a photograph of the core being transported.

##### 4.3 Wound film package test

The water content in the winding insulation surface layer is one of the most important indicators for transformer insulation capability. During the process from factory disassembling to transportation and then to onsite assembly, FATRAS mainly concentrates on preventing the moisture or water absorption of internal transformer parts. To confirm the moisture

Table 1 Comparison of FATRAS and a bank of three single-phase units for 500kV 1,000MVA

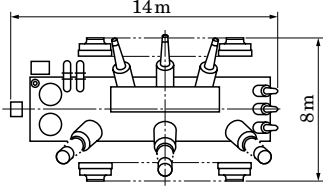
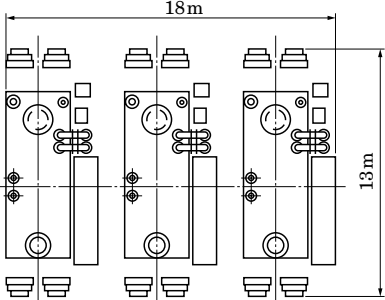
Item	FATRAS	Three single-phase units
Plane drawing		
Maximum transportation mass	(Core) 38t (26%)	146t (100%)
Installation area	112m <sup>2</sup> (48%)	234m <sup>2</sup> (100%)
Transportation method	Large low-floor trailer	Special freight car and trailer

Fig.2 Split structure of three-phase five-legged core

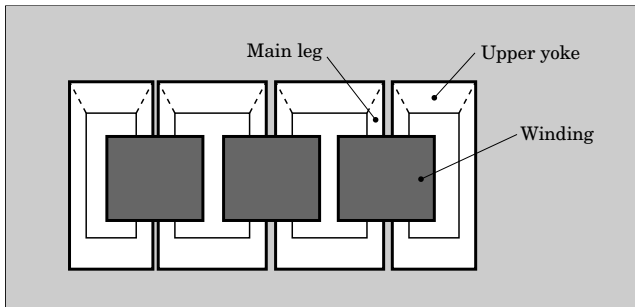


Fig.3 Winding assembly packaged with film

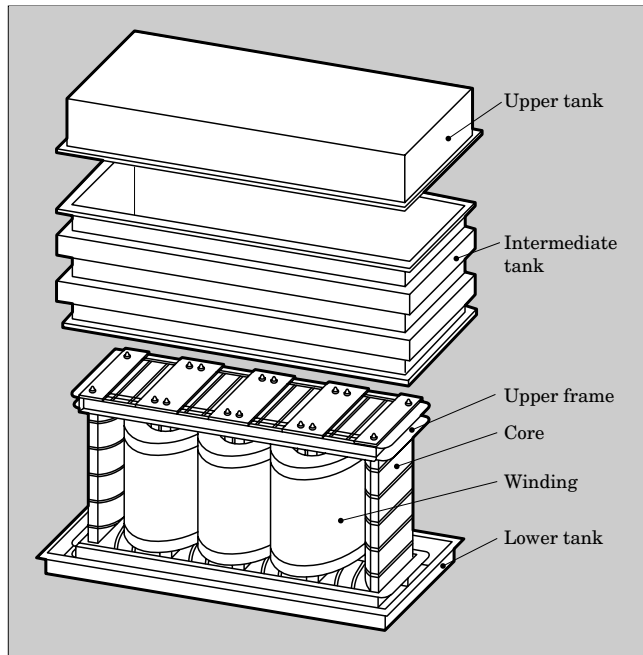


prevention effectiveness of the wound film package, the film was wrapped around an actual winding model. It was confirmed that there is no increase in water absorption during 60 days of an actual field test.

#### 4.4 Onsite assembly model test

With the actual size model, trial assembly of the core and windings was carried out using mobile cranes. The ease of reassembling and control for dimensional

Fig.4 Tank construction



tolerance were satisfactory. A no-load test and short-circuit impedance voltage test on the reassembled unit confirmed that the core and windings were in good condition.

## 5. Quality Control

### 5.1 Transportation

The core and windings are put in dedicated transportation tanks that are filled with dry air to prevent moisture absorption. During transportation by trailers, shock impact acceleration and trailer speed were continuously recorded. After delivery to the site, the deformation and rusting of the core parts as well as the displacement and deformation of the winding bodies were visually checked and verified that there

Fig.5 Testing of the five-legged three-phase core model (split type)



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Fig.6 Testing of the core component transportation



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Fig.7 System flow of high-vacuum refrigeration drying and hot-oil circulation drying

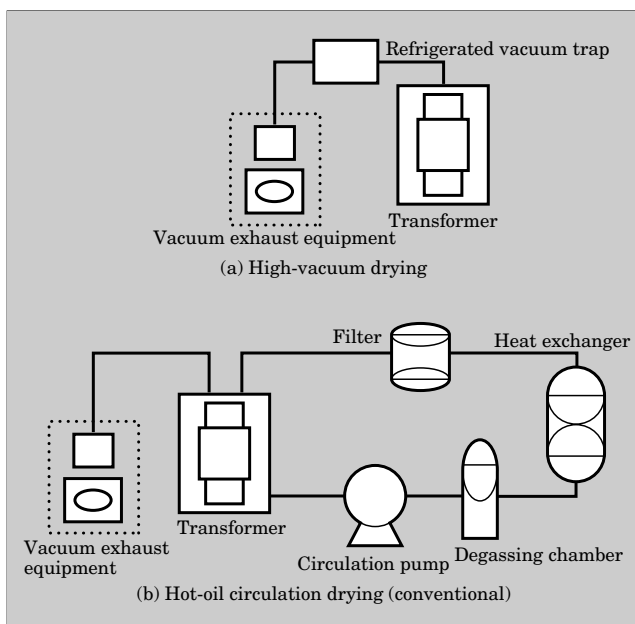


Fig.8 Dust-proof and air-conditioned building



AF906212

Table 2 Tests specific to FATRAS

Test item	Test method	Control value
Low voltage excitation test	Measure excitation current at low voltage	+30% or less of the factory data
Low voltage impedance test	Measure impedance at low voltage	±3% or less of the factory data
Long duration AC voltage withstand test	Measure internal partial discharge with ERA method	Not more than external noise (100 pC)

Fig.9 Onsite completed FATRAS



were no problems.

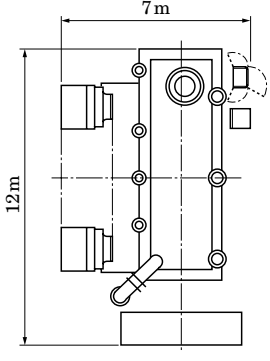
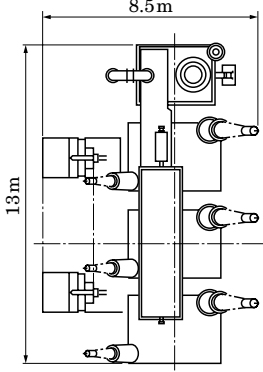
The control criteria for transportation are listed below.

- (1) Shock impact acceleration :  $29.4\text{m/s}^2$  {3G} or less (horizontal and vertical)
- (2) Trailer moving speed : 40km/h or less

## 5.2 Moisture prevention for the winding insulation material

To prevent moisture absorption, the windings remain packed in film from the time of factory disassembling until completion of onsite reassembling. By sampling pieces of insulation at each stage of the re-assembly, the moisture content was monitored. After reassembling is complete, an oil treatment was performed with the high vacuum refrigeration drying

Table 3 Comparison of FATRAS and the special three-phase unit for 275kV 250MVA

Item	FATRAS	Special three-phase unit
Plane drawing		
Total mass	235t (73%)	320t (100%)
Maximum transportation mass	20t (29%) (Core)	70t (100%)
Installation area	84m <sup>2</sup> (76%)	110m <sup>2</sup> (100%)
Transportation method	General low-floor trailer	Special freight car and large low-floor trailer

method. This method can avoid overheating of the system, reduce the required energy and save construction space as compared with the conventional hot-oil circulation drying method. Figure 7 shows a system diagram of the high-vacuum refrigeration drying and the hot-oil circulation drying.

### 5.3 Dust-proof air-conditioned building

The core and windings are reassembled onsite in a dust-proof air-conditioned building temporarily setup at the site. Environmental conditions inside this building are substantially equivalent to those at the factory, to maintain the same quality as at the factory. Specifications of this building are listed below.

- (1) Relative Humidity : 50% or less
- (2) Temperature : (23-9) to (23+7) °C
- (3) Dust quantity : 20CPM (counts per minute) or less

The ceiling of the building can be opened, and the heavy cores and windings hung down from outside of the building with a wrecker crane. Inside the building, a hoist crane is installed to move the upper yokes and the associated equipment.

### 5.4 Special tests for FATRAS

The most critical concern of FATRAS is reassembling the core and windings, and therefore, the tests shown in Table 2 were carried out in addition to normal onsite tests. The results of the low-voltage exciting test and the low-voltage impedance test were compared with the factory test data. A long duration AC voltage withstand test was also carried out satisfactorily.

## 6. Practical Application

A 275kV 100MVA and a 275kV 250MVA trans-

former were delivered as FATRAS in 1997, and have been operating successfully. The specifications of the 275kV 250MVA unit are listed below.

- (1) Type: three-phase 60Hz on-load tap-changing transformer
- (2) Cooling: ODAF(oil-directed air-forced)
- (3) Rated power: 250MVA
- (4) Rated voltage: 275/77kV
- (5) Sound level: 60 dB

Figure 9 shows the external view of the 275kV 250MVA transformer after completion of onsite reassembling. Table 3 compares FATRAS and the special three-phase transformer.

## 7. Conclusion

Practical application of FATRAS has been described. The results of the onsite tests have confirmed the same quality as the factory tests.

FATRAS has the following advantages.

- (1) The transportation cost can be greatly reduced because transportation measures such as road widening, bridge reinforcement, etc. are not needed.
- (2) FATRAS can reduce the installation space required in a substation, and therefore reduce the onsite construction cost.

Shipping and onsite installation costs will rise especially for transformers of hydropower stations in mountainous areas and of substations in urban and suburban areas, and therefore the demand for FATRAS will increase.

The authors intend to further enhance the performance and reliability of FATRAS in future.

# New Digital Relay System for Transformer Protection

Hiroshi Yamakawa  
Hirotooshi Sato  
Isao Chihara

## 1. Introduction

By fully utilizing a high-performance processing unit and a high-precision analog input unit, distinguished features of the new-generation digital protection relay, Fuji Electric has developed a transformer protection system with higher reliability and a simplified structure.

Largely improved operability and maintainability are achieved through the utilization of a portable human interface.

## 2. Features of the New-Generation Digital Protection Relay

### (1) Enhanced calculation processing ability

Processing capacity approximately 3 times greater than that of conventional relays is achieved by using the latest 32-bit microprocessor unit.

### (2) High-precision analog input circuit

Use of a 16-bit analog-to-digital converter and a 4,800Hz high-speed sampling technique has substantially improved the accuracy of the analog input circuit and expanded its dynamic range.

### (3) Comfortable human interface

By using a portable human interface (personal computer), operability and maintainability of the protection relay is improved and the system structure is simplified.

### (4) Enhanced automatic self-diagnostic function

Adding a failure-locating function to protection relays has improved the response to hardware breakdowns. In addition to detecting overloads, temporary failures can be prevented by implementing a retry of the automatic self-diagnostic test and restarting the microprocessor unit. Reliable detection of intermittent failures can be achieved by checking the frequency at which those failures occur.

### (5) Improved environment for software production

Development with the standard C language, a high-level software language, has resulted in improved reliability and productivity of the created software.

Table 1 Specifications of transformer protection relay system

Item	Conventional specifications	New specifications
Panel space	1 panel with 700mm width	1 panel with 700mm width
Configuration of processing unit	<ul style="list-style-type: none"> <li>○ Main detector for primary protection</li> <li>○ Main detector for back-up protection</li> <li>○ Fault detector</li> </ul>	<ul style="list-style-type: none"> <li>○ Main detector (integrated for primary and back-up protection)</li> <li>○ Fault detector</li> </ul>
Number of analog input channels	Main detector : 29 Fault detector : 27	Main detector : 23 Fault detector : 21
Full scale of analog input	Even for the same input, the full scale is different for each relay.	The full scale is the same among each relay.
Relay element	Main detector <ul style="list-style-type: none"> <li>○ Percentage differential relay (with 2nd harmonic restraint)</li> <li>○ High-level setting overcurrent relay</li> <li>○ Ground directional relay</li> <li>○ Phase distance relay (without countermeasure against low-order harmonics)</li> </ul> Fault detector <ul style="list-style-type: none"> <li>○ Percentage differential relay (with second harmonic restraint)</li> <li>○ High-level setting overcurrent relay</li> <li>○ Ground overvoltage relay</li> <li>○ Magnitude-of-change overcurrent relay</li> <li>○ Overcurrent relay</li> </ul> Other <ul style="list-style-type: none"> <li>○ Overload protection relay</li> </ul>	Main detector <ul style="list-style-type: none"> <li>○ Percentage differential relay (with 2nd harmonic restraint)</li> <li>○ High-level setting overcurrent relay</li> <li>○ Ground directional relay</li> <li>○ Phase distance relay (with countermeasure against low-order harmonics)</li> </ul> Fault detector <ul style="list-style-type: none"> <li>○ Percentage differential relay (without second harmonic restraint)</li> <li>○ Ground overvoltage relay</li> <li>○ Magnitude-of-change overcurrent relay</li> </ul> Other <ul style="list-style-type: none"> <li>○ Overload protection relay</li> </ul>
Human interface (HI)	Segment or LED display and ten-key (push button switch) input with operational display units mounted on the panel or a display-only tool.	A personal computer complying with OADG is used as a portable tool.

Fig.1 External view of transformer protection system

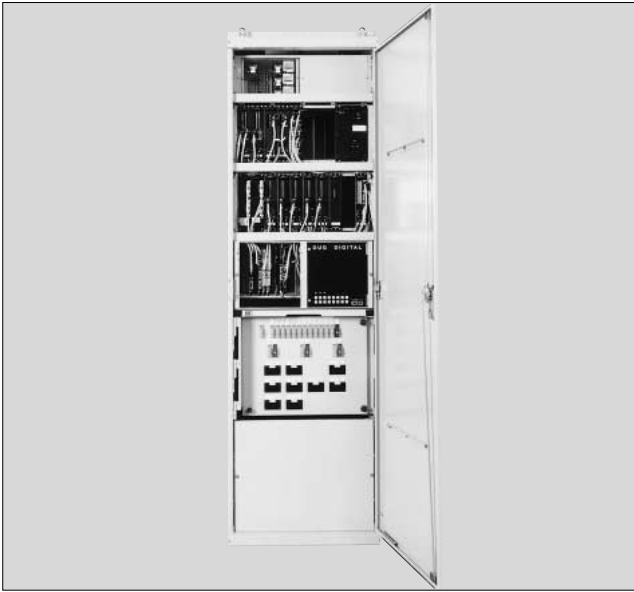


Table 2 Specifications of analog input unit

Processor	32-bit floating point DSP (digital signal processor)
Analog-to-digital converter	16-bit sampling ADC (analog-to-digital converter)
Sampling frequency	4,800 or 5,760Hz
Analog filter	3rd order LPF (low pass filter)
Number of input channels	16
Sample-and-hold element	Eliminated
DC-to-DC converter	5V/ ±15V
Data saving function	Save as temporary data

### 3. Structure and Specifications of the Transformer Protection System

#### 3.1 General structure

Table 1 lists a comparison of principal specifications of the developed 154kV transformer protection system with those of a conventional system. As can be seen, the panel space is equal to that of a conventional system but the internal system structure is simpler due to shared use of the units. An external view of the transformer protection system is shown in Fig. 1.

The processing unit structure has been modified from a conventional 3-unit configuration with a main detector for primary protection, a main detector for back-up protection and a fail-safe fault detector to a 2-unit configuration with a main detector (with integrated primary and back-up protection functions) and a fail-safe fault detector.

A personal computer conforming to OADG (personal computer Open Architecture Developers' Group) specifications is used as a portable tool for the human interface.

Fig.2 Configuration of analog input circuit (current transformer circuit)

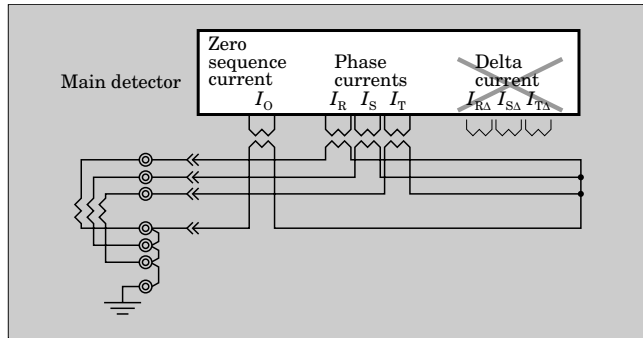


Table 3 Configuration of analog input circuit (current transformer circuit)

Protective relay element	Conventional specifications	New specifications
Primary protection : 87	Delta-connection is configured in CT (Current Transformer) secondary circuit and currents are input through specified auxiliary CTs.	Phase currents are input through auxiliary CTs shared by primary and back-up protection relays. Delta-current data for the 87-relay is generated by software processing.
Primary protection : 67G	Zero-phase current is synthesized with specified 3-winding auxiliary CT.	Zero-phase current is input from a residual circuit configured in the CT secondary circuit.
Back-up protection : 44S	Phase currents are input through specified auxiliary CTs.	Phase currents are input through auxiliary CTs shared by primary and back-up protection relays.
Overload protection : 57	To ensure relay accuracy, currents are input through specified CTs.	Primary and back-up protection relays are shared.

Fig.3 Tripping scheme with proportional differential current relays

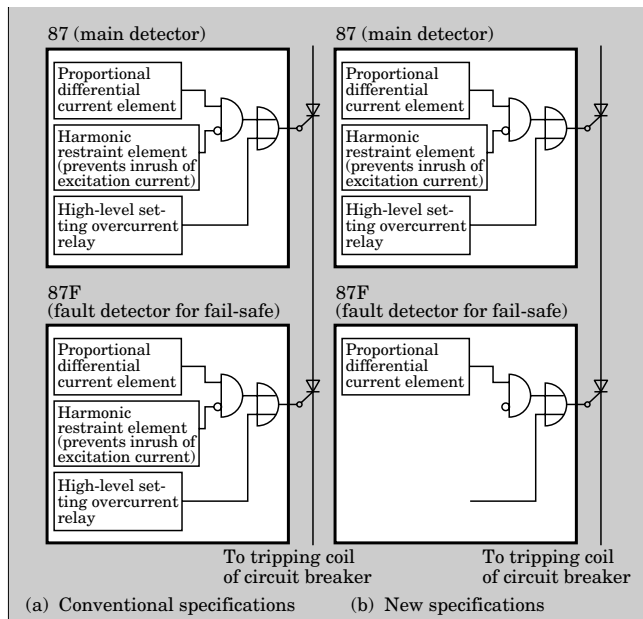
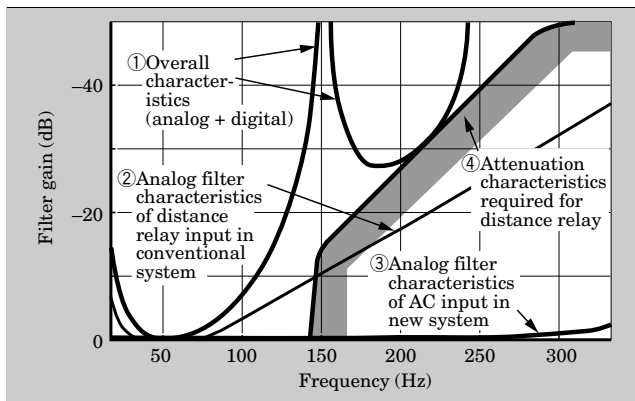




Fig.4 Example filter characteristics for distance relay



### 3.2 Analog input unit

#### 3.2.1 Shared use of analog input unit

The transformer protection system is configured with primary protection relays, back-up protection relays for the primary side (of the transformer), back-up protective relays for the secondary side and overload protection relays. In the past, due to dynamic range limitations, each relay element was equipped with its own analog input unit. Application of a 16-bit analog-to-digital converter and a 4,800Hz high-speed sampling technique to the analog input unit has ensured an accuracy of greater than 14-bit resolution (4 times the conventional accuracy) and has permitted shared use of the analog input for the primary, back-up and overload protection relays. Specifications of the analog input unit in the transformer protection system, the configuration of the analog input circuit (current transformer circuit) and a comparison of the circuit configuration with that of a conventional system are shown respectively in Table 2, Fig. 2 and Table 3.

#### 3.2.2 Automatic compensation of analog input unit with digital calculation

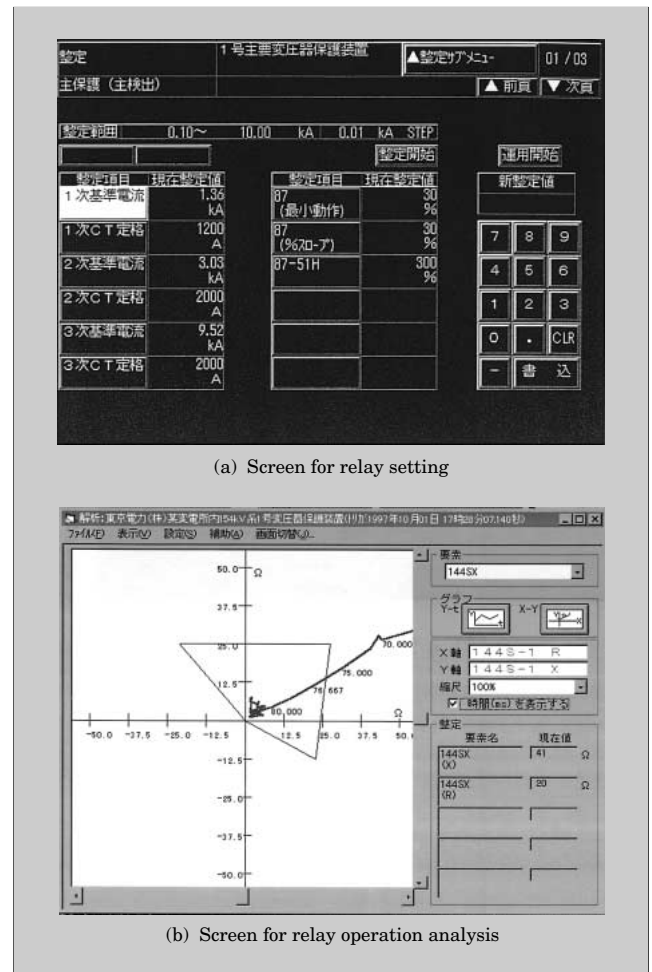
Although it is difficult to manually adjust a high precision 16-bit analog input unit, timing of the sampling between input channels must be compensated since the conventional sample-and-hold circuit has been eliminated. Automatic compensation with digital calculation corrects errors of the analog input circuit and has realized equivalently synchronized sampling of the input data.

### 3.3 Reassessment of protection relay characteristics

#### 3.3.1 Proportional differential relay

Conventionally, the 87F-relay of the fail-safe fault detector was configured in the same manner as the 87-relay of the main detector (for primary protection), with a proportional differential current element, a high-level setting overcurrent element and a harmonic restraint element to prevent relay malfunction caused by transformer excitation inrush current. Reassessment of the automatic self-diagnostic function has

Fig.5 Examples of human interface display screens



(a) Screen for relay setting

(b) Screen for relay operation analysis

enabled ANDed circuit breaker tripping by the main and fault detectors during a self-diagnostic test. This results in simplification of the fail-safe 87-F characteristics. Figure 3 shows a tripping scheme with the proportional differential 87-relay.

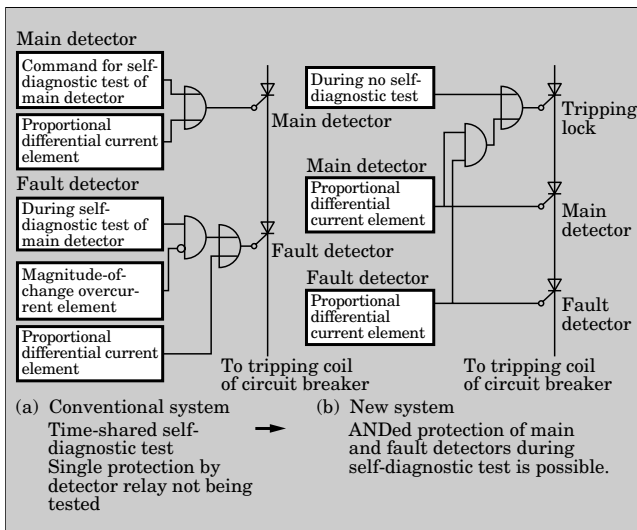
- (1) Elimination of the harmonic restraint element has resulted in a faster operating time of the proportional differential current element.
- (2) Since a faster operating time of the proportional differential current element allows inclusion of the former characteristics, the high-level setting overcurrent element has been eliminated.

#### 3.3.2 Distance relay

To improve the performance of distance measuring while low-order harmonic currents exist, and to share software with EHV transformer protection systems, a differential method with countermeasures against low-order harmonics is utilized in the distance protection 44S-relay for back-up protection.

Under the severe condition that “a fault current contains greater than 200% of the 2nd or higher order harmonics,” realization of favorable characteristics by combination of the relay principle and filters is required for this type of distance relay (Fig. 4 ①). For this reason, the AC input unit has been traditionally

Fig.6 Configuration of tripping circuit



provided with custom filter characteristics (functionality is achieved by sharing the attenuation characteristics with an analog filter = Fig. 4 ②), and a digital filter = difference between Fig. 4 ① and ②).

The new-generation digital relay filter, specialized to avoid quantization errors of the analog-to-digital converter, digitizes the filtering function for distance relay characteristics and is used as a shared analog filter in the newly specified system. This allows the AC input unit to be shared with other relay elements. Since the digital filter function is realized by software processing, system reliability is greatly improved and there is no unit-to-unit variation of characteristics, temperature variations or secular changes as in the case of analog filters.

Further, the addition to the distance relay of countermeasures against low-order harmonics has improved the performance of harmonics elimination and resulted in relatively smaller attenuation ratios of the analog and digital filters. This led to the realization of a high-speed relay whose operation time is 8 to 10ms shorter than that of conventional distance relays.

### 3.3.3 Fail-safe relay

Providing the ground overvoltage relay of the fault detector with a countermeasure against breaks in the voltage transformer's secondary circuit prevents erroneous system operation in case of voltage transformer failure, and eliminates the magnitude-of-change overcurrent relay in the main detector.

### 3.4 Human interface

Eliminating the built-in human interface unit reduces the cost of digital protection relays for installation in unattended substations that are equipped with a remote operation function. Modification of settings and verification of operation and relay failure are carried out by connecting a portable human interface

to a connector on the protection system panel when testing or restoring operation after a failure.

The human interface is a portable tool that utilizes a personal computer complying with OADG and running a Microsoft OS (Windows 3.1 or Windows 95). The functions are broadly divided into a write-data function for setting system values and a support function that indicates the operation status and analyzes failures. Figure 5 shows examples of the screen displays.

### 3.5 Remote operation system

Installation of a communication interface (Ethernet <Note> IEEE 802.3) allows operation of the following management and maintenance functions from remote control centers.

- (1) Modification and verification of setting values
- (2) Verification and reset of the number of automatic self-diagnostic tests
- (3) Verification of present managing status
- (4) Verification of relay operation status
- (5) Verification of hardware failure

### 3.6 Actions for fault during automatic self-diagnosis

As in conventional systems, static tripping elements (with operating speeds of 2 to 3ms) are used for the high-speed tripping of transformer internal faults.

Conventionally, an automatic test method has been used for the automatic self-diagnosis system of the analog input unit. However, a method of continuous monitoring has been utilized to improve operation reliability and simplify the automatic test circuit. This has also improved reliability of the tripping circuit.

- By adding a tripping-lock element, the system is configured not to trip due to the erroneous output of a single detector relay during self-diagnostic testing.
- During self-diagnostic testing, both the main and fault detectors continue to calculate the protective relay. When an internal fault occurs, the system instantaneously releases the tripping-lock and both detectors are logically ANDed to implement the tripping.

Figure 6 shows the configuration of the tripping circuit.

## 4. Conclusion

Practical results of the developed transformer protection system utilizing the new-generation digital relay have been reported. In the future, the results of this system will be applied to other systems.

<Note> Ethernet: A registered trademark of Xerox Corp., USA.

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