Present Status and Prospects for Substation Technology

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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 capacity transformer

Fuji Electric has supplied complete-bank-transportable transformers utilizing low-noise and all-in-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

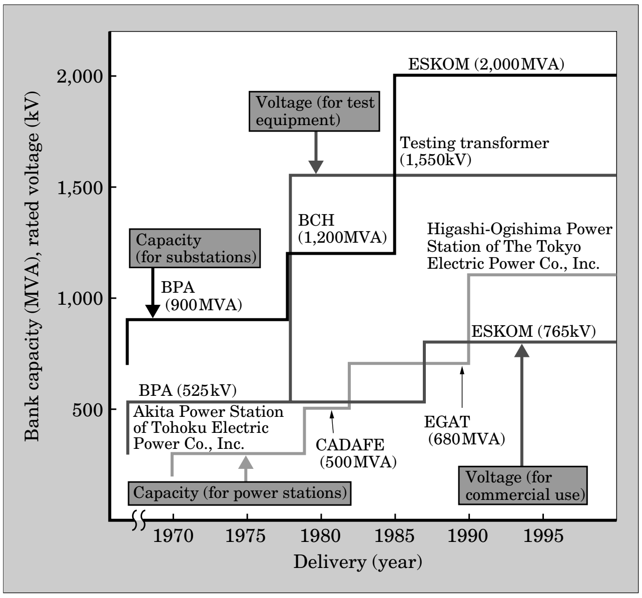

Fig.2 Main transformer being transported in a complete bank

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

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_6 gas-immersed or cast resin transformers are highly rated because of their safety, which is improved due to their nonflammable or flame-retarding characteristics. These types of transformers are increasingly used in urban substations.

Fuji Electric has developed SF_6 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_6 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_6 gas-immersed transformer and verified satisfactory results. Combining this with our previous production experience, we have established the technology for 154kV, 60MVA class SF_6 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

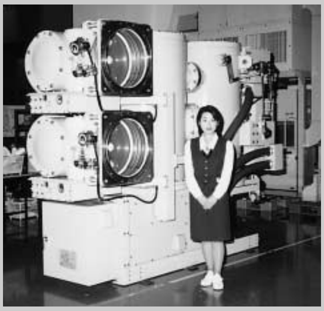
Rated short-time withstand current \ Rated voltage	72.5kV	123/145kV	170kV	245/300kV
31.5kA	SDH208 SDH108 SDK108			
40kA	SDA514		SDF120	
50kA	SDA530			

(a) Three-phase encapsulated and phase-segregated GIS

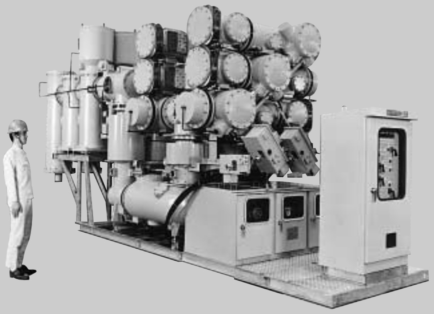
Rated short-time withstand current \ Rated voltage	7.2kV	24/36kV	72.5kV	72.5kV	123kV
12.5kA	SDV1007				
25kA	VG20/30				
25kA	SDD108				
31.5kA	SDD308				
31.5kA	SDD112				

CB type: VCB for 36 kV and below, GCB for 72.5 kV and above

(b) C-GIS



SDH208



SDA530

SDD308

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_6 gas circuit breaker

Fuji Electric developed a new 300kV, 50kA (single-breaking unit) SF_6 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 conventional 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

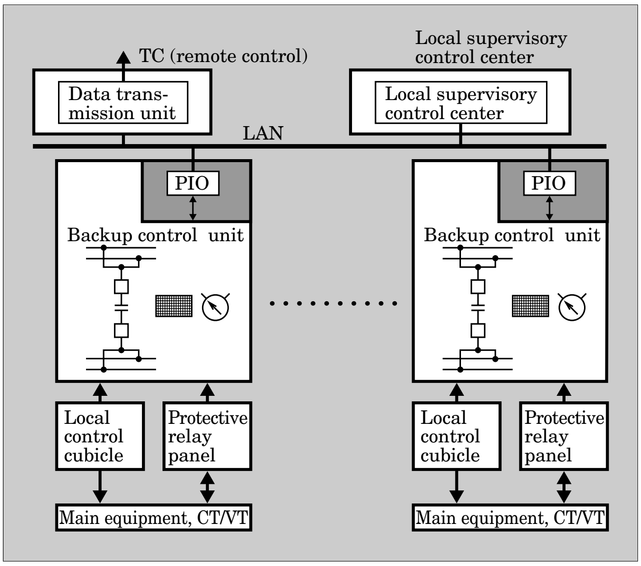
Substation supervisory control systems have made technical progress due to the application of microcomputer technology, coordination of advanced functions, performance of supervisory control and data acquisition systems (SCADA), application of LAN technology, and adoption of advanced human interface 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)

Item \ Classification / Type		Conventional digital relay: DUC	Conventional digital relay: DUF	Second- generation digital relay: 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 desirous 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_6 gas was specified as a greenhouse effect gas that would influence global warming. To decrease the amount of SF_6 gas used, a new product should be developed based on the concept of small size with less SF_6 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.

e-Front runners