# Development of 24-kV Switchgear with Multi-functional Vacuum Interrupters for Distribution

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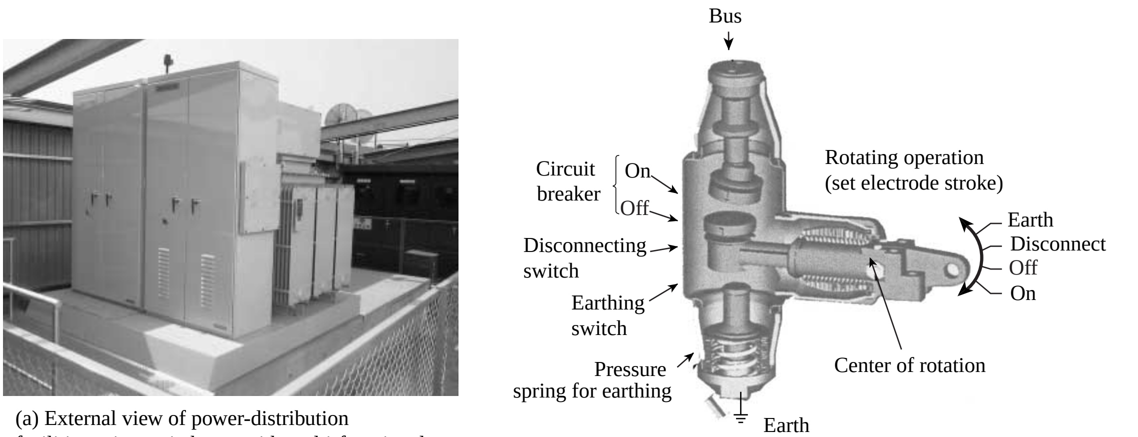
*OVERVIEW: Increasing demand for electric power in recent years as well as the difficulty of constructing new substations due to rising land prices have generated a need for boosting conventional 6-kV distribution. The relatively large size and high cost of 22-kV distributors compared to 6-kV ones, however, have provided an obstacle to their introduction. Against this background, Tokyo Electric Power Co., Inc. and Hitachi, Ltd. have jointly developed a switchgear with multi-functional vacuum interrupters enclosing a circuit breaker, a disconnecting switch, and an earthing switch. This switchgear is no larger than the 6-kV device and sufficiently satisfies initial objectives. Its reduced size has been achieved through a '4-position vacuum valve' that integrates a switching section consisting of a circuit breaker, a disconnecting switch, and an earthing switch. While the electrode inside the old vacuum valve could only move in a linear direction, the electrode in this new 4-position vacuum valve can move in an arc due to the development of barrel-shaped bellows. This arc movement provides a long stroke compared to that by linear movement, and has made it possible to establish four positions within the stroke and therefore achieve a significant reduction in equipment size. This switchgear with multi-functional vacuum interrupters has been delivered to 12 sites since December 1998 and its expansion to general private use and overseas markets is now being planned.*

## INTRODUCTION

AS the demand for electric power increases in urban areas where the consumption of power is concentrated, the cost of providing power is rising due to an insufficient number of sites for locating substations used in 6-kV distribution and to a congestion of distribution ducts. The need is therefore felt for boosting distribution voltage from 6.6 kV to 22 kV to increase capacity per circuit and thereby distribute power at near-load levels and supply power in a more




(a) External view of power-distribution facilities using switchgear with multi-functional vacuum interrupter

(b) Structure of 4-position vacuum valve

*Fig. 1— Distribution Facilities Delivered to Tokyo Electric Power Company for 'Zepp Tokyo.'*
*Distribution facilities (a) using 24-kV switchgear have been delivered to the 'Zepp Tokyo' concert hall. This switchgear employs a 4-position vacuum valve (b).*

efficient manner. Up to now, however, the large size and high cost of 22-kV equipment compared to 6-kV one have prevented this upgrading from taking place. In response to this problem, Tokyo Electric Power Company and Hitachi, Ltd. have jointly researched and developed switchgear with multi-functional vacuum interrupters that lowers the cost of 22-kV distribution equipment to 6-kV levels and results in a compact configuration.

This paper describes the development of this product and presents examples of its delivery.

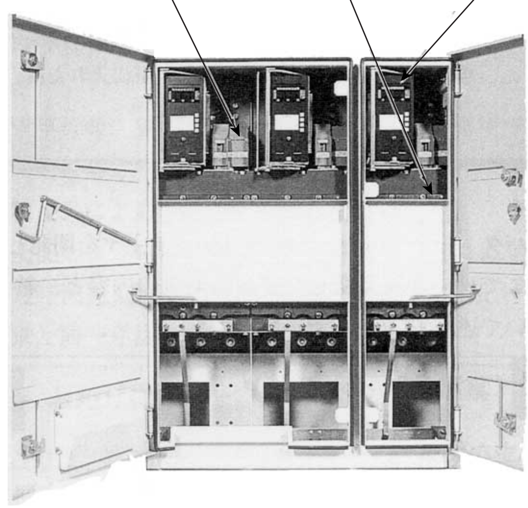
## SWITCHGEAR WITH MULTI-FUNCTIONAL VACUUM INTERRUPTERS

### Main Specifications

This switchgear houses main circuit switches in a grounded metal cabinet and incorporates switching equipment, protecting and controlling, and measuring device of main circuit current. Main specifications of this newly developed switchgear with multi-functional vacuum interrupters are listed in Table 1.

### External Dimensions

An external view of the switchgear with multi-functional vacuum interrupters is shown in Fig. 2. The external dimensions of this switchgear are established by Tokyo municipal regulations and are the same as 6-kV equipment currently installed along sides of roads. The interior houses switchgear consisting of a main-circuit section, control section, and other sections for three circuits, plus a mold-insulated bus for connecting these circuits.




ICU: intelligent control unit

*Fig. 2— External View of Switchgear with Multi-functional Vacuum Interrupters.*
*External dimensions of the switchgear are the same as 6-kV equipment: 1,100 (W) × 450 (D) × 1,450 (H) mm (1,500 mm high including the base section).*

TABLE 1. Main Specifications of Switchgear with Multi-functional Vacuum Interrupters
*Integration of switches and a composite insulation system are two major features of this switchgear.*

| Item | | Specifications |
|---|---|---|
| Type of switch | | Integrated circuit breaker, disconnecting switch, and earthing switch |
| Insulation system | | Composite insulation: vacuum, "$SF_6$ gas," and epoxy mold |
| Rated voltage | | 24 kV |
| Rated current | | 200A, 400A, 600A |
| Rated frequency/phase | | 50/60 Hz, 3-phase |
| Rated interrupting current | | 25 kA |
| Rated short-time current | | 25 kA 1s (main circuit, earthing circuit) |
| Voltage resistance | Commercial frequency | 50 kV (60 kV) |
| | Lightning impulse | 125 kV (145 kV) |

Figures in parentheses indicate voltage resistance between poles in the disconnecting switch.

### Configuration

The switchgear consists of (1) main-circuit sections enclosing three 4-position vacuum valves, which are connected each other by a mold-insulated bus; (2) operation panel for controlling these vacuum valves among the four positions of ON, OFF, disconnect, and earth; and (3) control sections featuring digital protection/metering equipment for protecting main circuits and monitoring current and voltage.

A cross section of the main-circuit section is shown in Fig. 3. This section consists of (1) a cable-side conducting section under the molded case for connecting cable heads; (2) molded current transformers and capacitors for detecting voltage; and (3) three 4-position vacuum valves enclosed in the molded case.

The design of the cable-side conducting section conforms to cable heads specified by IEEE (Institute of Electrical and Electronics Engineers) standards resulting in a uniform cable-head shape that up to now differed from one customer to another. This makes it

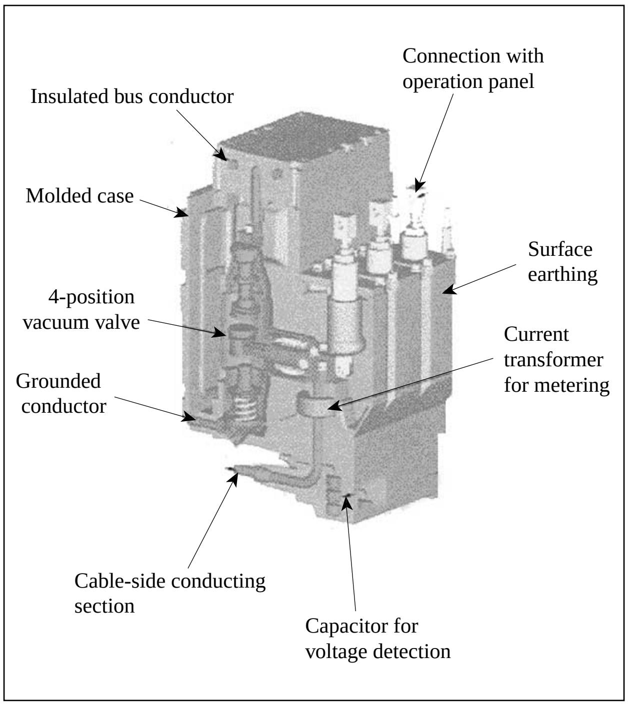



*Fig. 3— Cross Section of Main-circuit Section.*
*The entire surface of the epoxy-molded surface is coated with conductive paint and grounded to make maintenance operations safe.*

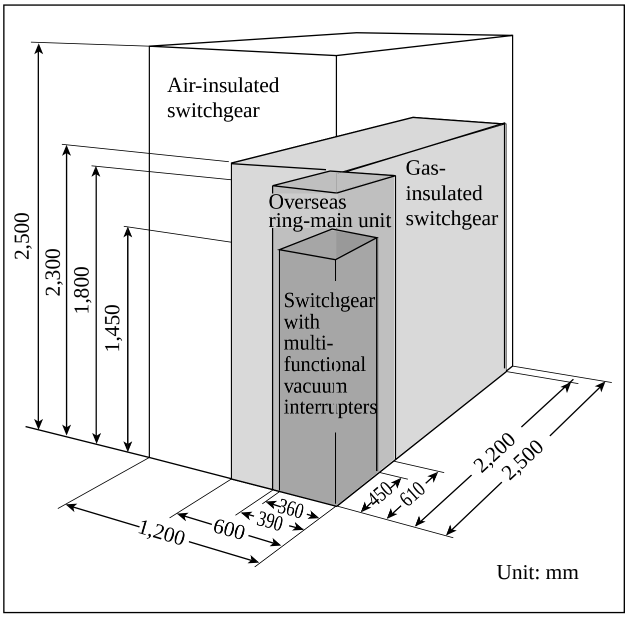



*Fig. 4— Comparison of Dimensions Between Newly Developed Switchgear and Past Products.*
*The floor space and volume of switchgear with multi-functional vacuum interrupters has been reduced to 1/18 and 1/30, respectively, that of air-insulated switchgear.*

possible to procure parts internationally and lower costs.

Insulation of main switchgear sections, that is, main circuits, earth, and poles, is accomplished by a small amount of $SF_6$ gas in the molded case and vacuum valves and by molded insulation plates between the vacuum valves. This composite insulation system makes for higher reliability.

Here, the amount of $SF_6$ gas, a factor in global warming, has been made several tenths of that used in gas-insulated switchgear for the sake of the environment.

### Comparison with Past Products

External dimensions are compared between the newly developed switchgear with multi-functional vacuum interrupters and past switchgear products in Fig. 4.

Other than the ring-main unit (described later), specifications of these past products assume the housing of one circuit consisting of a ‘circuit breaker + disconnecting switch + earthing switch.’ In addition to smaller dimensions, another feature of switchgear with multi-functional vacuum interrupters is cable connection to peripheral equipment. This provides more flexibility in equipment layout and also allows for a distributed configuration when installation restrictions in the case of an upgrade order prevent equipment from being installed together in one place.

## OVERVIEW OF SIZE-REDUCTION TECHNOLOGY

### 4-position Vacuum Valve

The structure of a 2-position vacuum valve used in ordinary circuit breakers and that of a 4-position vacuum valve used in switchgear with multi-functional vacuum interrupters are shown in Fig. 5.

The ordinary 2-position vacuum valve performs two functions, circuit making and circuit breaking, by operating a movable electrode in a vacuum container in an up/down linear motion between the two positions of ‘ON’ and ‘OFF.’ In contrast, the 4-position vacuum valve performs four functions, circuit making, circuit breaking, circuit disconnecting, and main-circuit earthing, by operating a movable electrode in a single vacuum container in an arc motion between the positions of ‘ON,’ ‘OFF,’ ‘disconnect,’ and ‘earth.’ This kind of vacuum valve is the first of its kind in the world.

By grouping a switch section consisting of a circuit breaker, a disconnecting switch, and an earthing switch into one vacuum valve, individual installation space for these devices and connection between them

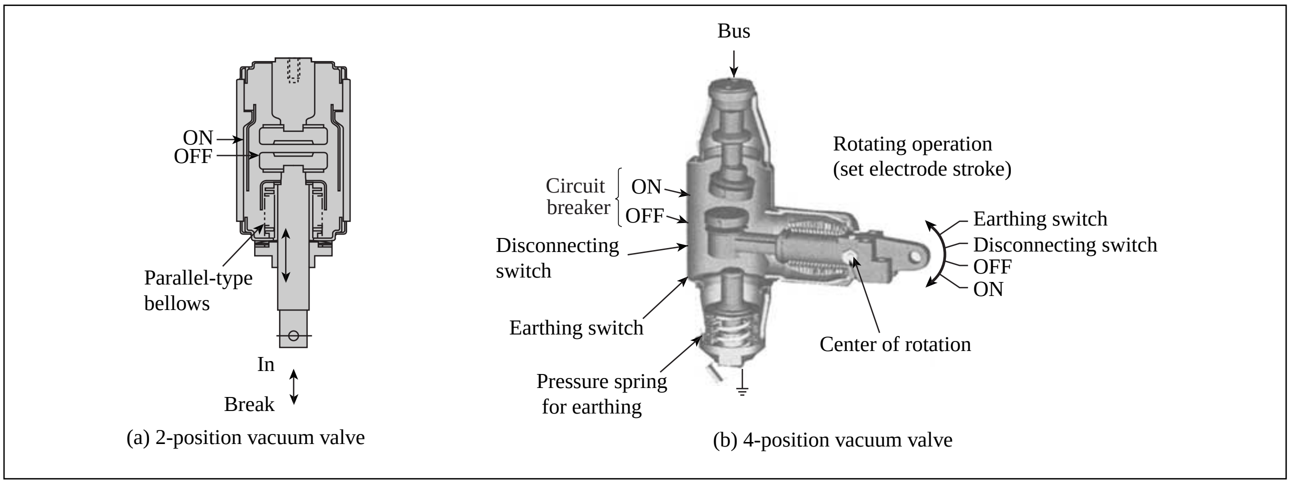



*Fig. 5— Structure of Vacuum Valves.*
*The vacuum valve has achieved four positions by giving the movable electrode arc motion instead of linear motion as used in the past.*

become unnecessary making for significant reduction in switchgear size and decease in number of parts.

Development of this 4-position vacuum valve required a bellows that could make this arc motion possible. A bellows is a flexible device here having the role of separating the vacuum in the vacuum valve from outside gas. This bellows is formed from stainless-steel sheets having a thickness of about 0.1 mm.

Because the movable electrode in an ordinary 2-position vacuum valve moves only in a linear direction, pleats of the bellows have the same shape and are parallel to each other. This configuration provides sufficient strength for linear expansion and contraction. If, however, we were to apply this kind of bellows to arc motion, stress analysis has revealed that the pleats would contact each other near the stationary section of the bellows generating stress about three times that during linear motion, as shown in Fig. 6 (a). A test on actual equipment, moreover, showed that the bellows would become damaged after several thousand rotations of arc motion resulting in a vacuum leak.

To solve this problem, we explored rotation angle and diameter, bellows length, and number of peaks as parameters and developed a 'barrel-shaped bellows' that could operate in an arc motion under roughly the same stress as that during linear motion.

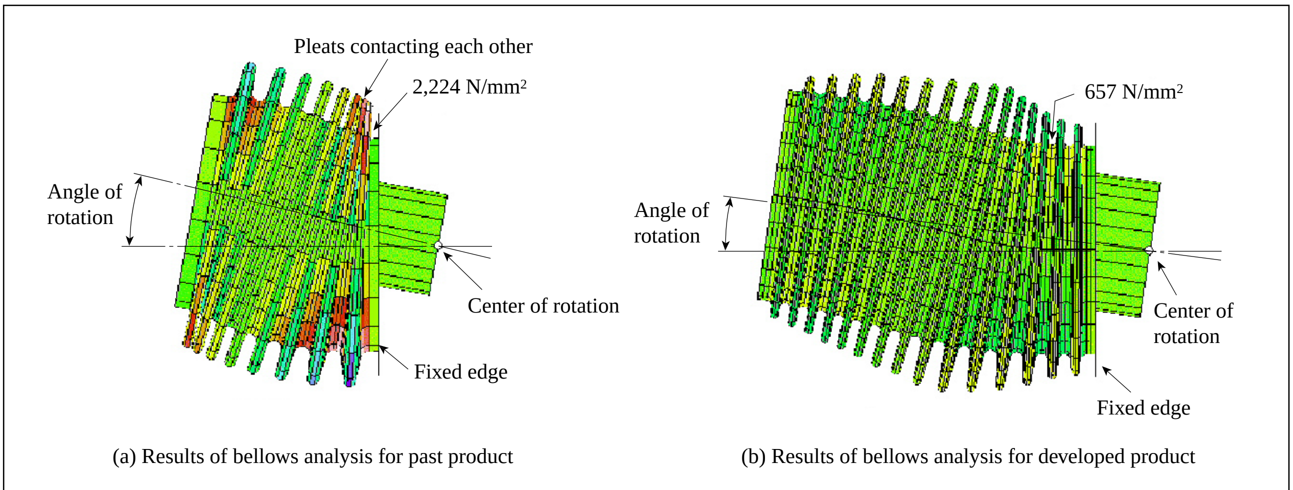



*Fig. 6— Comparison of Bellows Analysis Results for Past and Developed Products.*
*Stress was measured at the point where the bellows becomes constrained by its fixed edge when subjecting it to arc motion about the center of rotation shown.*


*Fig. 7— External View of ICU-S.*
*The ICU-S has been reduced in volume by about one-half compared to the conventional ICU-N.*

The results of stress analysis when subjecting bellows of the past product and that of the developed product to arc motion are shown in Fig. 6.

An operation test was performed with this barrel-shaped bellows and it was found that it could sufficiently endure usage conditions of real equipment. The results of this test also agreed well with lifetime prediction obtained by analysis.

As described above, the development of a barrel-shaped bellows has made it possible to manufacture vacuum valves that allow for rotating motion. On the other hand, a conventional vacuum valve features a nearly uniform electric arc when breaking the circuit since the electrodes are always aligned parallel to each other. The situation is different, however, in a 4-position vacuum valve. Because the movable electrode moves in an arc, the electrodes will become unaligned when breaking the circuit since they are designed to face each other directly when making contact. The pole-to-pole distance, moreover, will be significantly reduced at this time compared to equipment that of ordinarily air-insulated. As a result of the above, electromagnetic force between the poles increases and the arc when breaking the circuit spreads out in a non-uniform manner.

In response to this problem, we performed a study taking electrode materials, diameter, thickness and spiral groove structure as parameters. Specifically, we analyzed the electromagnetic force considering the effects of the interpole and current-path shape; observed arc activity by a high-speed camera; and compared the state of electrodes before and after circuit breaking. Using the results of this study, we optimized electrode-structure design and achieved target circuit-breaking performance.

### ICU

We employ an “ICU-S,” an upgraded version of a conventional digital relay, for the digital protection/metering equipment used in the control section. An external view of the ICU-S is shown in Fig. 7. Upgraded features are given below.
(1) Anti-noise performance has been improved.
(2) Protection-performing elements have been modified.
(3) Continuous monitoring function has been added.

Anti-noise performance has been improved in the following ways. First, surge absorbers have been inserted into the CT (Current Transformer) and PT (Potential Transformer) input circuits. Second, a metallic earth partition has been placed between input circuits and output circuits on the printed circuit board. In short, noise from the input circuits is now prevented from affecting the output circuits.

In regard to protection-performing elements, the zero-phase current-detection and voltage-detection sections in hardware have been upgraded to support switchgear with multi-functional vacuum interrupters and an add-on test was performed.

The new continuous monitoring function makes it possible to monitor each hardware functional block at all times and to record error codes corresponding to the location of a fault at the time of an abnormal occurrence. Time limits have also been set here to prevent erroneous judgment of transient noise that is even larger than levels established by noise tests.

## PRODUCT DEVELOPMENT

### Reliability Tests

As described in the previous sections, switchgear with multi-functional vacuum interrupters employs various new technologies including a vacuum valve and composite insulation using a molded case and gas. The JEM 1425, JEC 2300, JEM 1219, and JEC 2310 type approval tests were naturally performed for the switchgear, circuit breakers, load switchers, and disconnecting and earthing switches, respectively. The following reliability confirmation tests were also performed and sufficient levels of safety were verified.
(1) Bellows operation test
(2) Internal arc test
(3) Long-term vacuum-seal test

TABLE 2. Main Specifications of Amusement Establishment in Pallette Town
*To perform a circuit switchover at the time of a power outage, this system adopts an automatic circuit selection system that activates only when another circuit has voltage. The presence of voltage at the power-receive point can also be checked by voltage detection equipment.*

| Item | Description |
|---|---|
| Power receive system | Main-line/reserve-line power receive system |
| Receive voltage | 22 kV |
| Distribution voltage | 415 V |
| Facility capacity | 1,250 kVA × 2 units |
| Interrupting current | 25 kA |
| Protection and metering | ICU-S2 |

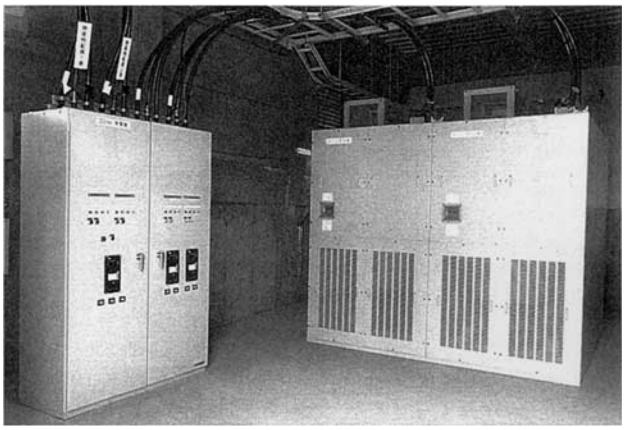


*Fig. 8— External View of Distribution Facilities for Amusement Establishment.*
*Switchgear with multi-functional vacuum interrupters is shown on the left and the transformer and low-voltage panel are shown on the right. Cables connect the switchgear and transformer.*

## Application to 22-kV and 415-V Distribution Facilities

Traditionally, facilities delivered to Tokyo Electric Power Company employed air-insulated disconnecting switches, earthing equipment, and fuses in the 22-kV distribution section and were integrated with the transformer and low-voltage panel. This resulted in large-size equipment, and the use of fuses in particular limited the capacity of each circuit and increased maintenance work.

For the above reasons, distribution facilities based on switchgear with multi-functional vacuum interrupters were proposed for an amusement establishment and three other sites within Pallette Town under the Koto branch of Tokyo Electric Power Company. These proposals emphasized a number of new features, namely, greater flexibility in facility layout due to compact equipment, increased facility capacity, and less maintenance work and improved reliability due to absence of fuses. These features were highly evaluated and the proposals accepted in all cases. In these orders, switchgear with multi-functional vacuum interrupters was delivered as a product for use as a distribution section in 22-kV and 415-V distribution facilities.

Specifications of distribution facilities delivered to an amusement establishment are listed in Table 2 and an external view of these facilities is shown in Fig. 8.

## Application to Distribution Towers

Due to the increasing demand for power in urban areas, the capacity of existing distribution towers, which are ranked as low-capacity substations, is increasingly becoming insufficient, and there is a growing need for large-capacity distribution towers. Soaring land prices, however, make it difficult to acquire sites, and new distribution towers regardless of capacity must have an installation space no greater than past towers.

Against this background, a distribution tower using switchgear with multi-functional vacuum interrupters has been delivered to the Choshi sales office of Tokyo Electric Power Company's Chiba branch office. Table 3 compares main specifications of this distribution tower with those of the old distribution tower delivered in 1993 by Hitachi, and Fig. 9 shows an external view of the newly delivered distribution tower.

In designing this distribution tower, the following measures were taken to reduce size, sound lower noise, and maintain operation during inclement weather conditions.

### (1) Reduction of installation area

In order to reduce installation area, 24-kV switchgear with multi-functional vacuum interrupters was employed not only for the 22-kV distribution section but also for the 6-kV distribution section. Transformer performance was also reexamined, and changing the oil-temperature rise limit from 55 to 60°C has made it possible to reduce the size of the heat-release section and achieve an installation area of 15 $m^2$.

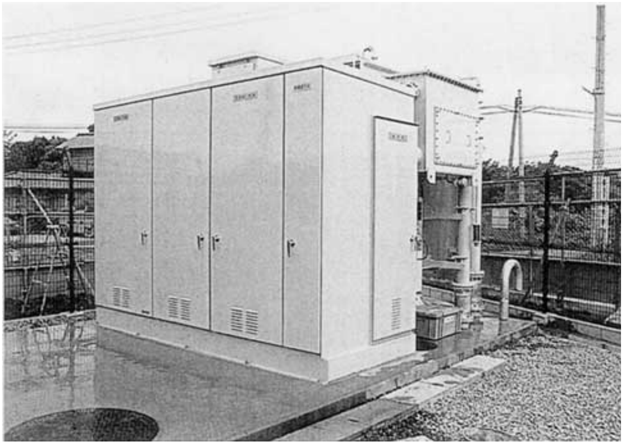


*Fig. 9— External View of Distribution Tower.*
*Switchgear with multi-functional vacuum interrupters is shown in the foreground in front of the 10-MVA transformer. External dimensions are 3.65 m (W) × 4.1 m (D) with an installation area of 15 m².*

TABLE 3. Comparison of Main Specifications Between Old and New Distribution Towers
*At 1.7 times the capacity of the old tower, the newly developed tower was installed within the same area. Tokyo Electric Power Company and Hitachi are now engaged in joint research aiming for an installation area of 10 m² with the following specifications of the newly developed product.*

| Item | Old tower | New tower |
|---|---|---|
| Receive voltage | 22 kV | Same |
| Distribution voltage | 6 kV | Same |
| Transformer capacity | 6 MVA | 10 MVA |
| Tap switcher during load | No | Yes |
| Noise | 70 dB (A) | 45 dB (A) |
| Operation room | No | Yes |
| Installation area | 15.4 m² | 15.0 m² |

(2) Reduction of sound noise

Taking the surrounding environment into account and considering that installation sites would also be located within urban areas, a 45 dB (A) super-low-noise transformer was designed. The figure of 45 dB corresponds to the level at which oscillating noise of the transformer can only be slightly heard at nearby points.

(3) Operation during inclement weather

Because a distribution tower is often operated manually during inclement weather conditions, an operation/test room has been incorporated in the tower to facilitate manual operation during such conditions.

## FUTURE DEVELOPMENTS

### Expansion to Private Demand

Switchgear with multi-functional vacuum interrupters has so far been delivered to 12 sites for use by power companies. Plans are now being considered, however, to develop a series of this switchgear for general private use concentrating on main-line/reserved-line power-receive systems, spot-network power-receive systems, and the like, and to propose such switchgear in accordance with user needs.

### Expansion to Overseas Markets

Considering that 11-kV and 22-kV ring-main distribution systems are common in Europe and Asia, switchgear with multi-functional vacuum interrupters is now being designed that can be used in this kind of distribution. Attention will therefore be given to expanding exports in the future, and it is thought that mass production that includes products for export should reduce costs.

### Application to Regular Networks

In downtown districts like Shinjuku and Ginza in Tokyo, power is distributed by the Regular Network (RNW) system. This system is 20 to 30 years old, however, and an equipment-aging survey has concluded that the facilities in question need to be upgraded. Many of these facilities, though, are installed underground below famous walkways. Their carry-in entrances, moreover, are only about 0.65 × 2.5 m, and any road excavation or broadening of these entrances would generate considerable expense. Light-duty RNW facilities using switchgear with multi-functional vacuum interrupters are therefore being proposed.

## CONCLUSIONS

This paper has described size-reduction technologies for switchgear with multi-functional vacuum interrupters for power distribution. Plans are being made to expand this switchgear to the upgrading of existing facilities in general private use, overseas markets, and RNW.

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