History of Power Transformers in Japan and Description of Related Historical Materials

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■ Abstract

The development history of transformer technology in Japan can be divided into three eras.

The first era, "from copying to domestic production" dates from the start of transformer production in 1893 through to the post-war era. Japanese technology started out being manufactured based on copies of overseas technology or produced through licenced technology contracts. By the 1920s, Japan had absorbed these technologies and grown to the point of becoming almost independent in its technology production; in the 1930s, Japan caught up to the level of technology that was available in the leading countries.

The next era, "breaking away from overseas technology" extends from the post-war era through to the mid-1970s. Japan's post-war rebuild period was a time of revitalising its technical cooperation with other countries and actively introducing new technology from overseas. This was followed by the economic boom and a growing demand for electricity, which led to the achievement of high-capacity technology at almost the same level as the technology available overseas, as well as the achievement of higher voltage 500kV transformers. High capacity is accompanied by the issue of flux leakage. Overseas technology offered no solutions to this issue, since Japan had reached almost the same level of technology as that which was available overseas; Japan had to solve the problem for itself. There was also the issue of countermeasures for the newly-introduced partial discharge testing for high voltage; this took ten years to solve. These solutions proved to be the trump card in revolutionising manufacturers' awareness of quality issues, bringing Japan to the forefront of other countries in terms of problem-solving.

The third and final era, "development of independent technology", dates from the late 1970s through to the present day. Frictional static electricity generated between insulators and transformer oil, used as a coolant in the 500kV transformer since 1972, caused flow electrification, leading to dielectric breakdown. The lessons learned while attempting to solve this issue proved very useful in later development of independent technology in Japan. Specific examples include the development of UHV transformers and UHV insulation technology within a far more limited scope of freight transport than other countries and the successful development of the world's first high-capacity gas-insulated transformer. These achievements were made by taking development back to the basics and down-to-earth validation. The new style of disassembled-for-transport transformer, which came about out of the very limited transportation conditions and the demand for high product reliability, was superior to the existing partition type transformers both in cost and in function and was expected to become widely adopted.

■ Profile

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March 1962	Graduated from the Department of Electrical Engineering, Faculty of Engineering, University of Tokyo
April 1962	Started working at Tokyo Shibaura Electric Co., Ltd. (now Toshiba Corp.) Worked on designing and developing power transformers for the next 40 years
October 1985	Awarded a degree from the University of Tokyo for research on the long-term insulation reliability of UHV transformers
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■ Contents

1. Introduction

To transmit high-capacity electricity from a power station to a distant point of consumption, electricity is sent out at high voltage due to the current capacity limitations of the power lines. Near the point of consumption, this voltage is stepped down and then transmitted to the consumer. Power transformers are used to convert the voltage. In order to coordinate power from many different power stations and to network this system, switching stations and substations are set up to supply consumers with reliable electricity with no power outages. The current transmission voltage in Japan is 500kV; the transformers that connect to this supply have the capacity to convert enough voltage to supply one million ordinary households each. While transformers have all kinds of uses, as outlined in the appendix, this report traces the history of technology and systematically examines power transformers, which have played a constant leading role in the transformer category.

This systematic examination categorises the main transformer technologies under discussion from five perspectives: high reliability, high capacity, high voltage, environmental issues and accessories, examining each perspective era by era. The points examined under the topic of high reliability include experimental verification, *lightning protected design* (technical terms in italics are explained in a simple glossary at the end), long-term reliability, maintenance and life span, *flow electrification*, voltage regulation, earthquake proofing and disaster proofing. The topic of high capacity includes transportation problems, as well as other issues, such as cores, coil winding and cooling. High voltage focuses on winding and insulation issues and touches on insulating materials and insulation treatments. The main points under environmental issues are noise and fire proofing. The accessories topic covers tap changers, coolers and radiators, *conservators* and bushing.

Below is a three-stage overview of transformers and their development history.

(1) From Copying to Domestic Production (Pre-War Transformer Technology)

(2) Breaking Away from Overseas Technology (Post-War Rebuild to 500kV Transformers)

(3) Development of Independent Technology (Overcoming Flow Eletricification and the Challenge of New Technology)

Chapter 2 provides an overview of the history of transformer development in Japan; Chapters 3 to 5 address the respective technological interests and technological developments in each era in detail. Chapter 6 re-examines the entire period from a systematisation perspective and traces the history of transformer technology development.

2. Overview of the Developmental History of Transformer Technology in Japan

2.1 From Copying to Domestic Production

(1) Early Transformers

Japanese transformer technology began with the copying of overseas products. In 1893, eight years after the transformer as we know it today first appeared, Miyoshi Electric started making its own copies of products from the United Kingdom. In 1900, engineers employed in American companies returned to Japan and started producing their own oil-filled transformers using American-style designs. While these first started out being used for lighting, there was an increasing demand for their use in power supply into the 1900s. As they began to be used for long-distance transmission of extra-high voltage, they needed to be capable of handling high voltage and high capacity. *Silicon steel sheets* and transformer oil began to be used from 1910, enabling transformers to meet these demands.

From 1911, technology from technical cooperation with overseas began to be incorporated into designs. Early transformers – even overseas ones – were mostly *shell-type* transformers, but in 1918, American company GE discovered an effective *barrier insulation* system using an insulation cylinder to separate the oil gap between coils, thereby enabling a shift to *core-type* transformers. Japan started making these as well and they later began to grow in their scope of application.

The 10MVA high-capacity transformer went into production in the 1920s, with 154kV transmissions beginning in 1923. At first, American-made transformers were used, but in 1926, Japan's first domestically produced 154kV transformer was put to use with a 6.667MVA unit for Nippon Electric Gifu Substation. The success of this transformer led to the later near-universal adoption of domestically-produced transformers. At this point, Japanese transformer technology could be regarded as standing on its own.

(2) Developments on the Korean Peninsula

The early Showa Period, in which there were major developments in Japanese transformers, was also the time in which the technology spread across to the Korean Peninsula and made progress there. This started with the supply of 36MVA units in 1928. Given the success of this arrangement, a succession of electrical facilities was established from 1935 onwards; the 220kV transformer, the first extremely-high voltage product in the East was completed in 1939, while the 100MVA for Sup'ung Power Station, with record-breaking capacity for a pre-war product, was completed in 1940. Large volumes of these transformers were sent to the Korean Peninsula and Manchuria until around 1943, when the war became too intense.

During this time, Japanese transformers came to stand equal with those from leading countries, both in terms of high voltage and high capacity. Without a doubt, the expansion into the Korean Peninsula and Manchuria significantly boosted Japanese transformer technology.

(3) Lightning Protected Design and Impulse Testing

The greatest matter of technical interest at this time was understanding the behaviour of transformer coils in lightning surges and the development of lightning-protected coils. A paper on the behaviour of transformer coils in lightning surges was published in Germany in 1915. From then on, research was carried out in various countries; research on lightning-protected coil structures was also being carried out at the same time. In Japan, there was a negative attitude towards adopting lightning-protected coils developed overseas; there was little advantage to it, since the transmission system was configured differently. While the coils used at the time emulated the structure of reinforced insulation at the ends of the coils, a standard winding system called *surge-proof winding* or *partially shielded winding* began to be adopted after a study of potential distribution carried out in the 1930s confirmed that this would have the same improved potential distribution effect as lightning-protected coils, even on the Japanese system. Impulse testing began on these lightning-protected design transformers in 1930 in the United States. It was first used in Japan in 1937 at 154kV and 18MVA for the Ministry of Railways. This was the first proof of the validity of the lightning-protected design transformers. Impulse testing became standard in 1945 as the war was ending.

2.2 Breaking Away from Overseas Technology

(1) The Appearance of Extremely-High Voltage (EHV) Transformers and the Introduction of Overseas Technology

The epoch of technology that immediately followed the war saw the beginning of 275kV transmission on the Shin-Hokuriku Trunk line, worked on by Kansai Electric Power Company. The transformers that were put into this system included pre-war technology as well as new, post-war technology. Given that these also underwent the standard impulse testing issued in 1945, this was a test of the technological capabilities of all companies involved; they were the combined result of all possible efforts from all sides at the time.

Technical cooperation with overseas had been suspended because of the war; it resumed in 1952 and new technology that had been worked on overseas during and after the war made its way into Japan. Some of this technology was worked out and implemented purely from information such as literature, some was worked out through collaboration with overseas partners and information gained on observation tours of overseas factories, and some was developed by own technology fostered during the war. This new technology poured into Japan from the mid-1950s to the 1960s. Many of these new technologies are still in use today.

The technology that was to have the greatest impact on the later development of the transformer was the adoption of *grain-oriented silicon steel sheets* introduced from the United States and the introduction of the *frame-shaped core* that used characteristics of new material. These had magnetic properties that were superior to the hot rolled silicon steel sheets that had been used since 1910 and could achieve high magnetic field strength with minimal excitation current. The magnetic field strength was also increased from 1.3T or less to 1.6-1.7T, which helped significantly to downsize the transformer.

(2) Increased Capacity for Power Station Transformers

The Japanese economy grew rapidly after the Korean War. The increased demand for electricity resulted in the successive establishment of high capacity thermal power stations. For the main equipment, such as generators, American-made products were usually used for the primary unit, while secondary and subsequent units were usually domestically-produced through licenced technology. However, the transformers were all domestically-produced from the start. Of course, many of these used new technology introduced from overseas.

The rate of capacity development for power station transformers was very quick, rapidly increasing from 200MVA in 1958 to 300MVA in 1960, 430MVA in 1963, 680MVA in 1966, 870MVA in 1971 and 1100MVA in 1973. Since this capacity speed was about the same as what was happening overseas, there were no solutions overseas to the issues that accompanied high capacity; Japan had to solve these on its own. In particular, Japan often had cases requiring *high impedance* in its configuration; making these transformers capable of high impedance added further complication to the issue of high capacity. In such cases, there was little to be gained from continuing technical cooperation and Japan gradually steered away from its reliance on licenced technology.

(3) High Capacity of Transformers for Transformer Substations and On-Load Tap Changing Devices

Once power stations were capable of high capacity, substation transformers had to be capable of high capacity as well. Combined with the strong demand from power companies to further reduce the interval between factory shipping and commencing operation, this meant a departure from disassembled-for-transport transformers, which were the norm for high-capacity units, to assembled-for-transport transformers. A *three-phase, five-limb core* was adopted, using grain-oriented silicon steel sheets to drastically reduce the size of the iron core and the hight of transportation. Special freight cars were put to use, making effective use of the dimensions in accordance with *rail transport limitations*. New lightning-protected coil structures and new insulating materials were adopted, meaning an improved coil space factor and a sudden rise in the capacity limits of assembled-for-transport transformers. By 1963, the technology had improved to the point that a 300 MVA transformer could be transported in the same space that could only have accommodated a 39 MVA transformer before the war.

In addition to the existing distribution transformers, there was also a need for power transformers to have *on-load tap changers* to improve the quality of the power. Around this time, German company MR was developing an on-load tap changer (LTC) built into the transformer tank. This received world-wide attention; its introduction and adoption in Japan through technical cooperation fulfilled the wishes of the power companies. The MR LTC is still being produced today through technical cooperation, albeit later, updated models of it. This is the only remaining instance of licenced technology in Japan’s transformer industry.

(4) The 500kV Transformer for Export and Partial Discharge Testing

Transformers increased in capacity and, when 275kV transformer technology took a steady hold in the 1960s, discussions began on the next stage of transmission voltage, inspired by the achievement of 400kV transmission in Europe. It was decided that the next transmission voltage would be 500kV. This official decision of 500kV spurred manufacturers into development; they carried out model validation assuming that freight cars would be the means of transportation. In 1966, a prototype was built and sent for demonstration testing to the Ultra High Voltage Laboratory in Takeyama on the Miura Peninsula. Since the aim was to build up an operating record overseas rather than adoption of the technology at home, Japanese manufacturers competed for overseas orders of 500kV and 400kV transformers for overseas schemes at the time; this succeeded in bringing in many orders for transformers from overseas. The transformer specifications immediately encountered insulation trouble on commencing 500kV transmission in the United States. Tests were introduced to monitor long-term *partial discharges* at a slightly higher voltage than the operating voltage. Countermeasures against partial discharge were unknown at the time, so it took a great deal of effort to solve; it took nearly another ten years to find the perfect solution.

(5) 500kV Transformers for Domestic Use

In the 1970s, Tokyo Electric Power decided on a 500kV transmission programme, determining transformer specifications, producing pre-testing equipment and carrying out testing. Development was more intense in Japan than in the West; Japan also had to work with the rail transport limitations, meaning a number of improvements had to be made to the existing export-market transformers in terms of coil structures and insulation. While specification decisions had to be made from an economic perspective, there was a major focus on reliability. Decisions were made on the positioning of the taps, the transformer configuration and also the test voltage. This reliability-focusing thinking continued until the end of the 1980s and had a huge impact on the direction of Japanese transformer technology.

Such was the introduction of the 500kV transformer. Insulation breakdown occurred during pre-implementation voltage impression testing in 1972, thereby delaying the commencement of 500kV operation a year until 1973. Further insulation breakdown occurred during voltage impression testing in 1974; a breakdown analysis and a detailed investigation of the actual transformers and model coils showed that the insulation breakdown was caused by a discharge of static electricity built up on the insulator through the flow of transformer oil.

2.3. Development of Independent Technology

(1) Overcoming Flow Electrification

The phenomenon of flow electrification in transformers was as yet unknown, so determining the cause of this was purely by trial and error. A number of models were built, from full-scale to basic, and conditions were varied to determine the causal factor. After two years of investigation, the leading cause of the build-up of static electricity was found to be the flow rate of the oil, the shape of oil duct and its susceptibility to electrification. The size of the AC electric field and the surface of the insulating material were also found to be factors, and countermeasures were put in place for each of these issues. The susceptibility of transformer oil to electrification was confirmed to be due to trace substances in the oil becoming activated by dissolved oxygen and copper ions in the oil and significantly altering the degree of electrification of the oil; to date, little more is known about this. This is one difficulty of using petroleum oil, which is a blended mixture in itself. Tests were carried out on the basic design of the problematic transformers to determine the extent to which this was happening, e.g. there was a new trend to try to determine another insulating structure, having traced it back to the electrical discharge. This contributed greatly to later technological developments in Japan.

(2) The Development of UHV Transformers and UHV Development Technology

Once Japan’s 500kV transmission network was established in the late 1970s, discussion turned to

UHV transmission – the next level of voltage – and development began. The idea was to develop a transformer that was subject to the same transportation limitations as the 500kV transformer, but was capable of twice the voltage. This was achieved through the use of new insulating material thanks to the aforementioned research tracing back to the electrical discharge phenomenon, as well as advances in computer-aided analysis technology, which was then becoming more powerful and more commonplace. A prototype was built at the end of the 1970s. Meanwhile, an investigation committee had been launched to work on implementing UHV transmission and investigate technology challenges. Throughout this time, various tests were being systematically carried out as more long-term reliability measures were being incorporated to withstand a higher level of operating stress than ever before. The results of these tests formed the basis for later decisions on test voltage in Japan.

However, the implementation of UHV was postponed due to changes in economic growth; manufacturers built the newly developed technology into 500kV models or lower, with the idea of downsizing these and reducing the amount of loss. This technology also succeeded in gaining some overseas orders for 765kV transformers.

(3) The Development of Gas-Insulated Transformers

The first gas-insulated transformer with SF_6 gas as the insulating material appeared as early as 1967. However, there was little demand at the time for non-flammable transformers and competition with PCB transformers meant even less demand was to follow. They reappeared in 1978 with film replacing the existing paper to insulate the conductors, which greatly improved the impulse withstand voltage, which had been lacking. Just as gas-insulated switchgear (GIS) was becoming more widely used, there was a rise in demand for gas-insulated transformers for underground substations and for underground railways, as they allowed for more compact substations. Later improvements in coil cooling systems, etc. enabled the production of self-cooling models up to 30MVA; these even began to be used by power companies for distribution.

Initiatives to increase the capacity of gas-insulated transformers began in the United States, with the idea of developing and implementing 300MVA class transformers in the early 1980s. However, those plans were interrupted and development was cut short. Investigation into increased capacity began around that time in Japan, leading on from the development that had started in the United States, with various companies working on developing a transformer that used a liquid called perfluorocarbon as the coolant and PET film and SF_6 for insulation. As the various companies worked on their developments in their own way, Toshiba completed a 154kV, 200MVA transformer for Tokyo Electric Power in 1989. This was followed by 275kV, 250MVA and 300MVA transformers produced by Hitachi, Toshiba and Mitsubishi respectively in 1990. These differed completely in structure from the existing oil-immersed transformers and had many technical issues needing to be solved, but these hurdles were systematically cleared. They passed reliability verification and were put to practical use, the result of the basic technology capability that had taken root since the flow electrification incidents.

However, although gas-insulated transformers that used this cooling method did exist, they were more expensive than the existing oil-immersed transformers because they required special cooling equipment and expensive coolants; it was therefore difficult to bring them into general use. Nevertheless, Toshiba had developed *shunt reactors* needed for underground substations and had researched gas cooling because the transformer cooling method of incorporating a cooling panel would not work for cooling the cores of blocked shunt reactors. During the course of that research, Toshiba found that gas cooling could also be used on 300MVA class transformers. This was successfully achieved by establishing the technology to analyse gas flow through coils, developing the technology to equalise heat distribution and combining this with existing high-pressure, high-capacity gas blowers, high pressure gas vessels and thermal upgraded insulation; in 1994, 300MVA gass cooling transformers were supplied to the Tokyo Electric Power Higashi-Shinjuku Substation. The cost of the transformer was kept down by using SF_6 for cooling and for insulation. There were benefits to having gas devices for the entire substation and the cost margin narrowed to the point that it was no longer less attractive than oil-immersed transformers. After that, gas-insulated transformers replaced the existing oil-immersed transformers as the main transformers used in underground substations.

(4) UHV Demonstration Testing Equipment

During the 1990s and the early 21st century, the UHV programme that had been put on hold in the 1980s came back to life at Tokyo Electric Power, with a sudden plan to carry out two years of verification testing from 1995. Full-scale model verification and transformer specification decisions were carried out on the basis of production that had stopped in the 1980s; the testing equipment ordered successively from Hitachi, Toshiba and Mitsubishi comprised 1050/525/147kV transformers with a bank capacity of 3000MVA, the same rating as expected in actual machines in the future. Technically, it was completed in 1993 using the insulating technology developed in the 1980s, but it then underwent two years of testing at the Shin-Haruna Substation. Several new issues were encountered during that process, making this testing process significant.

The plan at the time was to commence UHV transmission at the beginning of the 21st century, but the current schedule was suspended due to the slump in power demand when the bubble economy burst. It is not clear when UHV will be implemented.

(5) Changes in Transport Conditions and the New Disassembled-for-Transport Transformers

Since the appearance of the 500kV transformers, power companies in Japan have placed a strong demand on reliability, avoiding dealing with the internal workings of the transformer on site as much as possible. By the late 1970s, downsizing of the main transformer had progressed to the point that the use of a transport cover, which was then replaced by a proper cover on site, was hardly seen, much less the disassembled-for-transport system practised until the 1960s. Meanwhile, transformers were expected to reproduce factory quality on site and were freighted in their factory inspection state; where transportation conditions were tough, the number of transformer partitions increased, as did the number of corresponding cases. Site conditions and transport conditions for substations, particularly pumped storage stations, gradually worsened; despite an increase in transformer partitions, the cost of transportation drastically increased, meaning certain measures had to be taken. The first companies to work on this issue were Kansai Electric Power and Mitsubishi Electric.

They proposed a new disassembled-for-transport system, which included various ingenious ideas, such as packing all the coils together in a film pack, using a moisture-absorption-eliminating structure for disassembly and onsite reassembly, cutting down the level of dryness onsite and emulating factory conditions for the iron core and onsite assembly. This method was later adopted by various companies; it became standard practice to have improved iron cores, dust-proof working chambers, field test requirements, test case investigations and field testing equipment. By 1994, the 500kV, 1000MVA transformer, which had been three single-phase structure, was three-phase. Besides being far cheaper, it also had the benefits of less installation space and less loss, providing the impetus for later expansions in its application. Its applications are thought to continue to expand in future, regardless of how it is transported.

3. From Copying to Domestic Production (Pre-War Transformer Technology) (1)

3.1. Early Transformers

(1) The Age of Copying

The transformers that first appeared in Japan were 500-lamp, 125Hz, 1000V, 30kVA generators imported by Osaka Electric Light Company from the United States in 1889. From when AC distribution began, British-made transformers were imported.

The transformer had its origins with Michael Faraday's validation of electromagnetic induction in 1831. However, the basic closed magnetic loop core structure of today's transformers was invented by an engineer at Ganz Electric Works in Hungary in 1885. This was displayed at an exhibition held in Budapest that year and began to be hugely successful as a power source for electric lights[2]. This invention triggered the expansion of the AC power system, forming the basis for the later high-capacity, high-voltage electricity supply systems. Photo 3.1 shows a model of Faraday's electromagnetic induction experiment; Photo 3.2 shows the first transformer displayed at the exhibition in Budapest.

Photo 3.1. A Model of Faraday's Electromagnetic Induction Coil (1831)

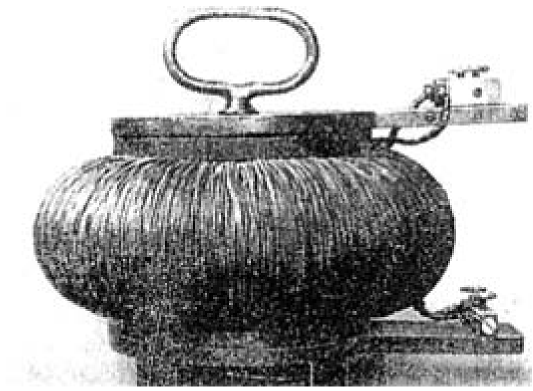


Photo 3.2. The Shell-Type Transformer Displayed at an Exhibition in Budapest by Ganz (1885)

While the first domestically-produced transformer in Japan is said to have been an 1893 copy made by Miyoshi Electric, founded by Shoichi Miyoshi in 1883, of a British-made transformer, there is no detailed record of this, since Miyoshi Electric closed down in 1898. The following year, in 1894, Toshiba's predecessor Shibaura Engineering Works started producing single-phase 0.375-10kVA and three-phase 1-30kVA transformers to step down from 1000V or 2000V to 100V, emulating a product made by British company Ferranti. This product was displayed at the Fourth National Industrial Exhibition in Kyoto in 1895. Since it was air-cooled, the transformer was long and thin, so it was known as the 'pagoda tower'. The shape of it cannot be confirmed, as there are no surviving photographs of it. Photo 3.3 shows a contemporary product made by Ferranti[3]. Meidensha Corporation also started producing transformers in 1897 with a 50-100 lamp capacity of 10 candlepower.

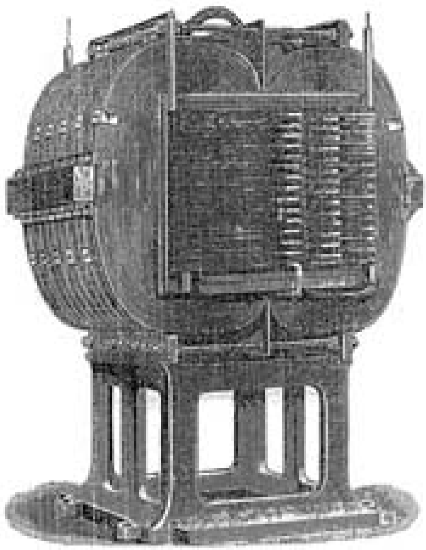


Photo 3.3. Ferranti's 150hp Shell-Type Transformer Supplied to a London Substation (1891)

(2) The Start of Oil-Immersed Transformers

The end of the age of copying and the transition into independent design came when Zentaro Iijima, who had been employed by US company Wagner Electric Corporation, returned to Japan to work for Shibaura Engineering Works and introduced an independent design for an American-style oil-immersed transformer. As well as distribution transformers, Iijima also branched out into the design and manufacture of testing transformers and extra-high-voltage transformers. In 1903, he produced a 50kV, 4kVA testing transformer (shown in Photo 3.4), which was displayed at the World's Fair in St Louis the following year, winning a gold medal and invigorating the Japanese electrical industry.

Photo 3.4. Shibaura 50kV Testing Transformer Exhibited at the 1904 World's Fair

In 1905, he produced the first 11kV, 150kVA extra-high-voltage transformer for Kofu Electric. *Extra-high voltage* had been introduced to Japan in 1899, using American-made transformers. Fig. 3.1 shows the progress of domestically-produced transformers in terms of high voltage and high capacity. A 22kV, 250kVA transformer was produced in 1906; in 1907, Tokyo Electric Light Company started its first 47-mile long-distance 55kV, 15MW transmission from Komahashi Power Station to Waseda, using a 2000kVA transformer made by American company GE. In 1908, Shibaura Engineering Works supplied Hakone Hydroelectric Power with a 44kV, 500kVA transformer. In 1909, a *shell-type*, water-cooled, single phase, 44kV, 1500kVA transformer supplied by Shibaura Engineering Works to Yokohama Electric's Hodogaya substation, a ground-breaking domestically-produced product for the day, used *vacuum drying* for the first time[(4)]. Special lectures were held at the Institute of Electrical Engineers of Japan (IEEJ); records at the time show production up of extra-high-voltage transformers until 1910 as 34 15350kVA transformers at 30kV, 75 7815kVA transformers at 20kV, and 19 417kVA transformers at 10kV. The number of transformers completed by

Shibaura Engineering Works is based on a contemporary testing ledger examined by the author; there were found to be 3800 mostly distribution transformers, meaning the company already had quite a substantial production capacity at the time.

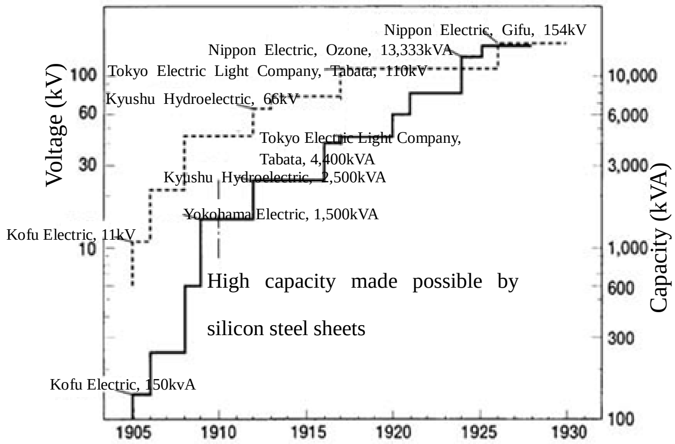


Fig. 3.1. High Capacity and High Voltage Progress of Early Transformers

Hitachi started manufacturing transformers in 1908 and Mitsubishi in 1910, marking the beginning of significant progress in Japan’s domestic production of transformers. Photo 3.5 shows a transformer thought to be the oldest patented evaporation-cooled, oil-immersed, self-cooling, single phase, 60Hz, 100kVA, 12/13.2kV-3.3kV extra-high-voltage transformer in existence, made in 1910 for Shinano Electric.

Photo 3.5. The Oldest Extra-High-Voltage Transformer in Existence (13.2kV, 100kVA; made in 1910 by Shibaura for Shinano Electric)

This transformer has water droplets forced to the tank surface; as the water evaporates, the evaporation temperature dissipates a lot of heat. This was a novel attempt at high capacity in an age when radiators had not yet been implemented. This was a priceless resource at a time when thin mild steel was still being used for the core. Photo 3.6 shows Hitachi’s first transformer supplied to Hitachi Mine in 1910, which was then used for another 50 years.

Photo 3.6. 5kVA Transformer for Hitachi Mine (made in 1910 by Hitachi)

(3) Establishing a Network of Transformer Manufacturers

Shibaura Engineering Works entered into technical cooperation with American company GE in 1909 and began incorporating the new technology into its designs from 1911. In 1910, silicon steel sheets were imported from the United Kingdom and trialled on pole-mount transformers. In 1911, silicon steel plates made by American company Allegheny were imported along with transformer oil from Vacuum Oil Company. Transformers of 3300V or higher were oil-immersed, while 2200V or lower transformers were the dry type. Transformers of 500kVA or higher were shell-type transformers.

In 1911, Hitachi completed a single-phase, water-cooled, 1500kVA transformer. Shibaura produced a 66kV, 2500kVA transformer in 1912 and a 22kV, 4000kVA transformer in 1916 for Kyushu Hydroelectric, as well as 110kV, 4400kVA transformers for Inawashiro Hydroelectric and Tokyo Electric Light Company's Tabata substation in 1917. Records leading up to the Great Kanto Earthquake of 1923 show that a single-phase, 66kV, 6000kVA transformer appeared in 1920, followed by a three-phase, 66kV, 8000kVA transformer the following year. In any case, the first high-capacity, high-voltage products of the time were imports from the United States; domestically-produced products followed two to six years later.

Up until this point, high-capacity transformers were shell-type transformers, as previously mentioned; however, in response to GE policy changes in 1919, Shibaura started making *core-type* medium-capacity transformers, which gradually began to expand in their scope of application.

Mitsubishi entered into a technical cooperation with American company WH in 1923; Fuji Electric did the same with German company Siemens in 1925. Both companies started manufacturing transformers, thereby establishing a Japanese network of transformer manufacturers.

(4) Summary of the Early Developmental Period

The early developmental period of transformers in Japan was the time leading up to the Great Kanto Earthquake of 1923. The first transformers started out as copies of products imported from overseas; these developed as far as the use of independent technology learned in the United States to produce extra-high-voltage oil-immersed transformers. With the import of industrially-produced silicon steel sheets and insulating oil in the 1910s and an increase in electricity usage, transformers developed further to handle higher capacity and higher voltage. There was an increase in the number of transformer manufacturers during this period, as well as the beginning of technical cooperation with overseas companies. While the earliest recorded products were generally imports from overseas, domestic production began within two to six years of their introduction. This period saw the introduction of not only the existing shell-type transformers, but also the technology for core-type transformers, which gradually expanded in scope to become the main technology used in the industry – also during this period. In other words, this early period dates from the introduction of transformers through to the establishment of a transformer manufacturing network and the beginnings of independence.

3.2. Domestic Production of Technology

(1) Completion of the 154kV Transformer

Production of the first high-capacity transformers over 10MVA started with the single-phase, water-cooled, 77kV, 13.333MVA transformer made in 1924 for the Nippon Electric Ozone Substation; this was followed by an 80kV, 15MVA transformer for Toho Electric the following year. Transmission of 154kV began in Japan in 1923 between Keihin Electric's Ryushima Power Station and the Totsuka Substation, while the first domestically-produced 154kV transformer was a single-phase, 6.667MVA units made (by Shibaura) for the Nippon Electric Gifu Substation in 1926. In the foreword of Shigenari Miyamoto's *Henatsuki no Shimpo (Progress of the Transformer)* [(1)], Sadaji Momota, former president of IEEJ, recalls that "this transformer was the first 150kV-level transformer produced in Japan and it had very good operating performance; when you think about the fact that nearly all 150kV-level transformers were domestically-produced and that there were only one or two overseas products available, this is a very significant achievement in the history of the transformer in Japan." This was followed by seven 10MVA transformers for the Yanagigawara Power Station and seven 13.333MVA transformers for the Komaki Power Station. Photo 3.7 shows a 165kV, 12.5MVA transformer for the Showa Electric Sasazu Substation; this was the highest tap voltage product available at the time.

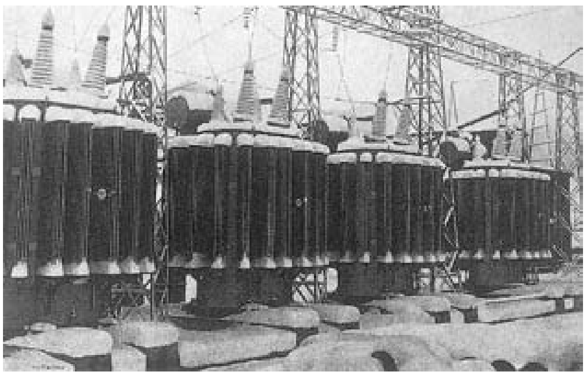


Photo 3.7. A 165kV, 12.5MVA Transformer for Showa Electric Sasazu Substation (1928, made by Hitachi)

The existing 10MVA-level transformers had to be disassembled for transport; they were reassembled on site and re-dried. The new 77kV, 10MVA transformer built for the Daido Electric Shinyodogawa Power Station in 1926 was transported by sea already assembled and immersed in oil. This was the first time to transport a heavy item in this manner and it was the forerunner of the later assembled-for-transport system. The exterior is shown in Photo 3.8.

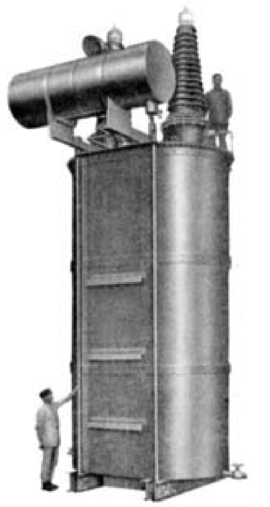


Photo 3.8. Assembled-for-Transport 10 MVA Water-Cooled Transformer for Daido Electric Shinyodogawa Power Station (made in 1926 by Shibaura)

(2) Cooling Methods

The main cooling method used in the high capacity transformers at this time was water cooling, whereby water pipes were mounted on the upper inside of the tank and the water flow would directly cool the oil. As cooling design technology advanced, developments were made in large-scale radiator manufacturing technology around the mid-1920s. This expanded the scope of application for natural circulation self-cooling methods, whereby the oil would cool inside a radiator. The radiator was invented and put to practical use by Stanley of the USA in 1916; it became more widely adopted around this time because advances in welding technology for thin steel sheets reduced the amount of oil leaks from the welded areas. A record 10MVA self-cooling transformer was supplied to Ujigawa Electric in 1927; the following year in 1928, nine single-phase 22MVA, 140kV-87kV-11kV three-winding transformers were supplied to the Showa Electric Yao Substation (made by Shibaura). This was world-record capacity, beating the American record at the time.

(3) Insulating Material

Insulating materials at the time were improving worldwide as the electric supply voltage increased. For example, cotton thread was used as an early insulator for coil conductor; manila paper tape wrapping began to be used from around 1915. Laminated insulating cylinders made from paper hardened with resin began to be used from around 1910; the insulating barrier formed by concentrically arranging these insulating cylinders along the oil channel provided effective insulation. With this understanding, GE switched from the previous *shell-type* transformers to *core-type* transformers in 1918. Following suit, Shibaura also switched to core-type transformers, as mentioned previously. In 1928, an L-shaped insulator called a flanged collar started being used to increase the insulation at the ends of the coils.

3.3. Development on the Korean Peninsula and the Success of the Transformer

(1) Hydroelectricity Development Programme on the Korean Peninsula

Japan Nitrogenous Fertilizer planned a programme for developing hydroelectric power on the Korean Peninsula. Changes to the Yalu River basin would allow for a vast volume of water and a high drop. It began with a 300,000kW development on the Pujon River; the first power station had a three-phase, water-cooled, 115kV, 36MVA transformer, supplied (by Shibaura) in 1928. At the time, this was a world-record-breaking water-cooled transformer. Since a crane lift could not be used during factory assembly, the interior was assembled atop the base tank, which was situated in a pit, with an ingenious method of construction whereby the tank was cut into slices and then fitted in place.

With the development project on the Pujon River being more successful than expected, development started on the Changjin River. Seven three-phase, water-cooled, 110kV, 40MVA transformers were supplied to the first power station in 1935; three three-phase, water-cooled, 110kV, 45MVA transformers were supplied to the second power station in 1936; three three-phase, water-cooled, 154kV, 60MVA transformers were supplied to the second power station in 1937. Work commenced on the Heochun River, with the first extremery-high voltage power supply of 220kV in the East. The first Heochun River power station was completed in 1939, with a three-phase, water-cooled, 220kV, 80MVA transformer supplied by Shibaura. This had a total mass of 225 tons and was the world’s highest-capacity water-cooled transformer. Photo 3.9 shows the exterior of the first 220kV transformer.

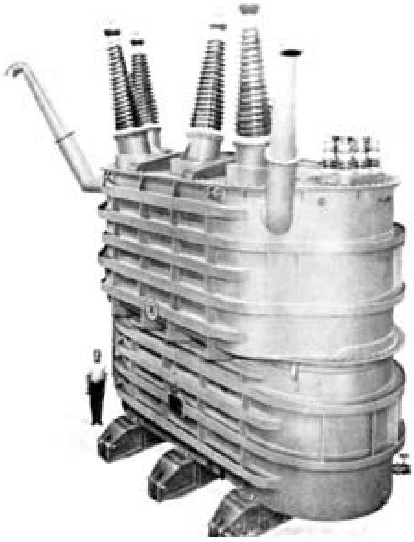


Photo 3.9. Japan's First 220kV, 80MVA Transformer for Heochun River (made in 1939 by Shibaura)

Besides this, the second power station had a water-cooled, 40MVA transformer; there was a three-phase, water-cooled, 80MVA transformer in Dongheungnam as a receiving substation, a three-phase, forced-oil, water-cooled, 80MVA transformer in Ryonghung and a three-phase, oil-immersed, forced-air cooled, 80MVA transformer in Chongjin. This transformer for Chongjin was Japan's first transformer with a separately mounted radiator. Since this 220kV power line was Japan's first attempt at an EHV system, many experts were called in to test it, with many tests carried out, such as *arc suppression test*. Instead of the existing *voltage application test* for dielectric strength, an *induced withstand voltage test* was carried out for the first time on a transformer.

Next, development commenced on the Yalu River itself, starting with the magnificent Sup'ung Power Station, equipped with seven (and one spare) of the world's highest-capacity 100MVA transformers. While some of the generators were ordered from Germany, the transformers were all produced and supplied in Japan (by Toshiba). These 100MVA transformers operated at 50Hz as well as having a 50Hz/60Hz duplexer; they were completed in 1940-1941 and had the highest capacity in the world at the time, although Japan was nine years behind Germany with the 15/230kV, three-phase, forced-oil, water-cooled style of transformer[5] (Photo 3.10).

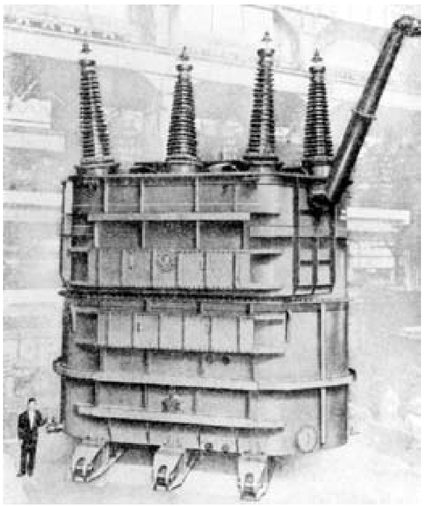


Photo 3.10. The World's Highest-Capacity 230kV, 100MVA, Water-Cooled Transformer for Yalu River Sup'ung Power Station (made in 1940 by Toshiba)

The coils reached a height of 3.5m; insulating cylinders of these dimensions could not be produced domestically; instead, insulating paper specially ordered from Oji Paper Company's factory in Sakhalin was used. Factory manufacturing and testing equipment had to be remodelled and expanded to manufacture these. The three receiving substations had six three-phase, forced-oil, forced-air cooled, 220kV-66kV, 100MVA transformers; this was the first finned unit cooler system made in Japan (Photo 3.11). Fig. 3.2 shows the developments in transformer capacity on the Korean Peninsula during the Showa Period.

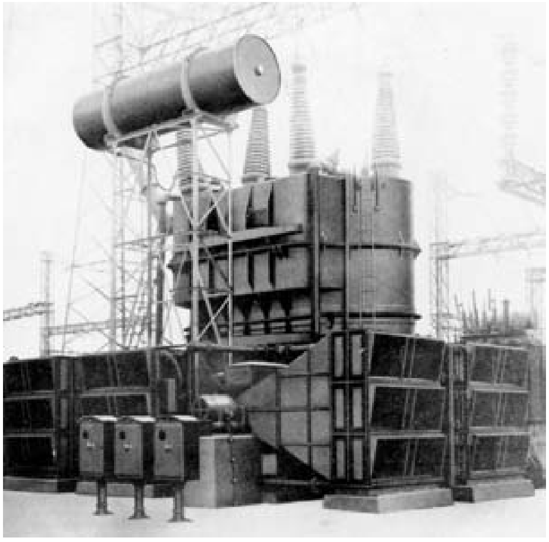


Photo 3.11. Forced-Oil, Forced-Air-Cooled, 220kV, 100MVA Transformer (made in 1941 by Toshiba)

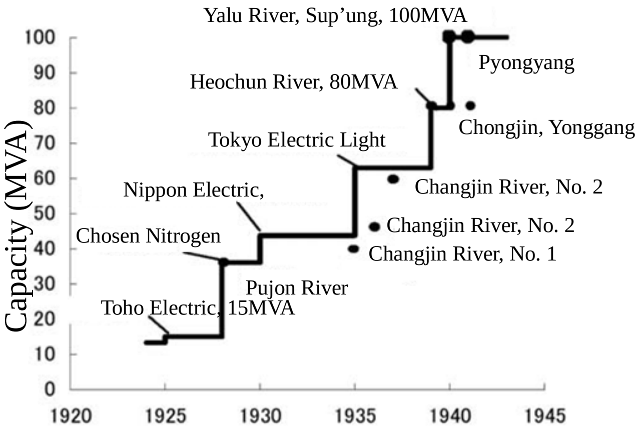


Fig. 3.2. Developments in Transformer Capacity on the Korean Peninsula during the Showa Period

(2) Advances in Cooling

In Japan, 10MVA was surpassed for the first time in 1924 in a transformer for Nippon Electric's Ozone Substation, while a record 22MVA self-cooling transformer was completed in 1928 for the Showa Electric Yao Substation. A 72kV, 43.75MVA transformer for Nippon Electric's Tsurumi Thermal Power Station in 1930 used a forced-oil pump to circulate the oil, while the radiator used special alloy steel and ocean water for cooling. In 1935, a 66kV, 63MVA transformer was completed for the Tokyo Electric Light Company Tsurumi Thermal No. 1 Power Station, while in 1938, a 154kV, 50MVA transformer was completed for the Tokyo Electric Light Company Wadabori Substation. This transformer took Japan's record for forced-oil, forced-air cooled systems, with a special radiator comprising steel pipes wound in a solenoid shape and a vertical blower positioned in the centre (Photo 3.12). Forced-oil, forced-air cooling systems were mainly developed in Europe; the first one in Japan was on an 80kV, 12.5MVA transformer for Kansai Power Distribution in 1926.

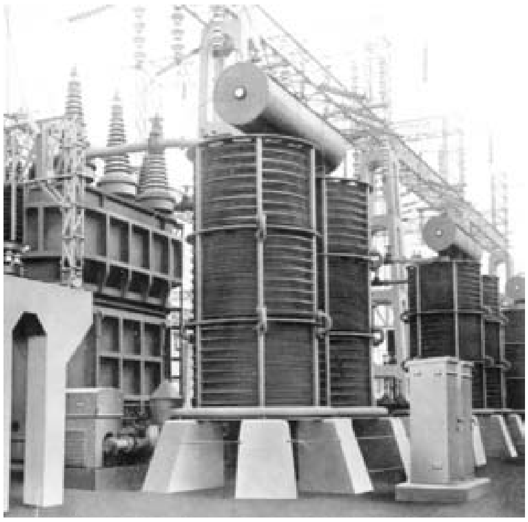


Photo 3.12. The First Forced-Oil, Forced-Air-Cooled Transformer
(Tokyo Electric Light Company Wadabori Substation 154kV, 50MVA, made in 1938 by Shibaura)

(3) Lightning-Protected Design

Major technical considerations in the pre-war era were the development of potential vibration analyses and lightning-protected coils for lightning surges and also impulse testing. In 1915, German engineer Karl Wagner published a paper in EuM journal entitled "The Penetration of Travelling Waves into a Coil with Inter-Winding Capacitance," presenting the basic ideas on the internal potential vibration of transformer windings[6]. This prompted a series of research in the United States, Germany and Japan from 1915 to 1920, which established the fact that transformer windings can be considered to be distributed constant circuits. A lot of results were published in Japan during this time, particularly by universities. A specific design for a lightning-protected coil structure to reduce winding vibration was first proposed in 1921 by Risaburō Torikai of Kyoto University in an article in the UK Journal of the Institution of Electrical Engineers (JIEE) entitled “Abnormal Pressure-rise in Transformer and its Remedy”[7]. Rather than distributing series capacitance and earth capacitance uniformly, this design aligned initial capacitance and final capacitance by adjusting the earth capacitance in inverse proportion to the distance from the ground and adjusting the series capacitance in proportion to that distance, thereby preventing oscillation and improving the electrical gradient. While this theory was not immediately applied to transformers, GE drew some attention with its announcement of a non-resonant transformer in 1929. Although all kinds of lightning-protected structures were being proposed throughout the world at the time, winding structures such as those typified by the *non-resonant transformer* were not used in Japan, because the *neutral points* were not directly grounded, meaning a high-resistance ground. The measures generally taken followed those from around 1920, such as reinforcing the insulation at the ends of the winding circuit. However, other methods gradually began to adopted, such as *surge-proof winding, partially shielded winding and multiple cylindrical winding*.

(4) Impulse Testing

In 1926, the reinforcing of line insulation in a 220kV system in Pennsylvania, United States, prompted a discussion on *insulation coordination*. This argument made it necessary to prove that transformers were resistant to impulse surge voltages greater than the coordination gap. In 1930, GE carried out the first impulse testing. This prompted the establishment of a standardisation committee in the United States, with the first draft presented in 1933. Meanwhile, Japan established an investigation committee in 1936 to investigate impulse surge testing, with the first draft presented to the committee in 1937. At the same time, Japanese Government Railways recorded in a specification document that the transformers used in the Senju Power Station and Musashi-Sakai Substation, then under construction, should have “insulation against surge waves in the form of coordination gaps, bushing and windings to improve its proof strength.” Impulse surge testing had to be implemented to ensure this. Impulse testing was implemented in Japan on a single-phase, 18MVA, 154kV transformer (made by Shibaura) in 1937[8]. The exterior is shown in Photo 3.13, the interior in Photo 3.14 and the impulse voltage generator at the time in Photo 3.15. Around 1938, the testing was also implemented on 31MVA transformers for the Senju Power Station. These transformers had the aforementioned standard design of the time, with reinforced insulation at the ends of the windings, but despite some issues arising with poor materials used in the wooden pole for operating the tap changer, they passed the test, proving the validity of the lightning-protected insulation design used at the time. In 1940, the first extremely-high voltage impulse test was carried out on a 230kV transformer bound for Manchuria.

However, around this time, a trend emerged towards using the lightning-protected coil structure in Japan as well. Mitsubishi implemented surge potential distribution measurements in 1933 and promptly used *surge-proof windings* developed by WH in 1932 to a 165kV, 7.5MVA transformer for Taiwan Electric. While Shibaura did not place the entire coil in a large shield, as GE did with its *non-resonant transformer* in 1934, potential distribution measurements confirmed the effectiveness of its *partially shielded winding (rib shield winding)*, which covered the ends of its coils in a partial shield to adequately provide the same effect. This system was used in a 154kV, 39MVA transformer for the Tokyo Electric Light Company Shinano River Power Station in 1939 and was later used universally. In 1941, Hitachi also confirmed the effectiveness of the partially shielded winding in a prototype.

Shibaura took note of a *non-resonant winding (multiple cylindrical winding)* developed by German company AEG in 1937 and from 1940 began its own developments and applied for testing trasformers which are grounded in neutral and arc-suppression reactor’s coil winding. However, it was not until after the war that this was used in a power transformer.

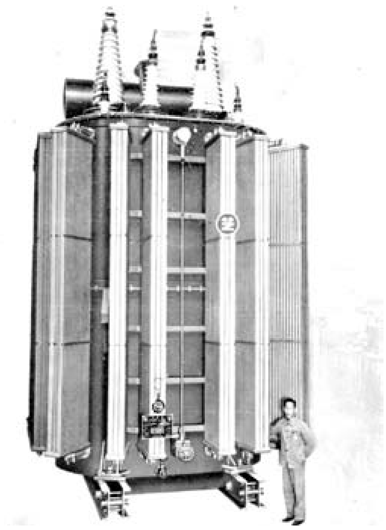


Photo 3.13. The 154kV, 18MVA Transformer for the Japanese Government Railways Musashi-Sakai Substation (made in 1937 by Shibaura), on which the First Impulse Testing was Carried Out

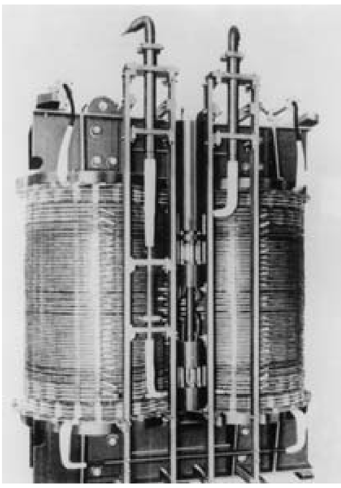


Photo 3.14. Photograph of the Interior of the 18MVA Musashi-Sakai Transformer

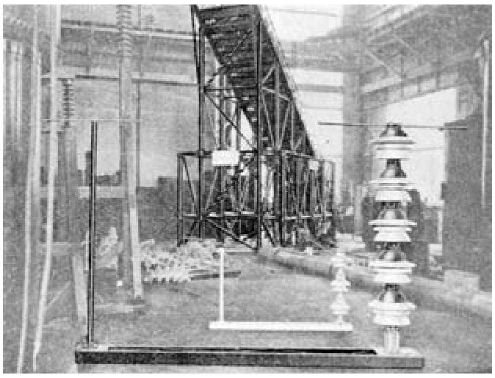


Photo 3.15. An Early Impulse Test Voltage Generator

(5) Transformer Regulations

A set of draft transformer impulse surge testing regulations was announced in 1940; following a draft revision in 1944, these were issued as JEC-110 in 1945. JEC-106 on impulse surge tests and JEC-107 on impulse surge measurement techniques were also issued in 1944.

The process of formulating regulations for transformers began with the establishment in 1922 of JEC-9, which prescribed electrical equipment standard regulations for all electronic goods, including rotators. This was followed by the establishment of JEC-36 in 1934, comprising standard regulations for transformers, induced voltage regulators and reactors, and in which transformers were targeted separately. During the war, JEC-36Z was issued as a wartime standard; this relaxed the limits on temperature rise. Japan Standard JES31 was issued in 1926 for standard transformers. A Japanese Engineering Standard (JES) was issued in 1941 on transformer oil. The aforementioned JEC-110 added impulse testing to JEC-36 as a type test.

(6) Assembled Rail Transport

Assembled transportation of transformers in Japan lagged far behind Europe. Most of the high capacity transformers at the time, including the aforementioned record-breaking products in Korea, were disassembled for transportation, then reassembled and dried on site, which meant a lot of time was spent working onsite. However, to reduce the amount of time spent on onsite reassembly, Japan set its sights on assembled transportation. As mentioned previously, the 10MVA high-capacity transformer built for the Daido Electric Shinyodogawa Power Station in 1926 was the first high-capacity transformer to be transported by sea already assembled and immersed in oil. In 1928, a 7.5MVA transformer built for the Toho Electric Najima Substation was transported by rail already assembled and immersed in oil; in 1932, single-phase, 77kV, 22MVA transformers bound for the Toho Electric Kizu and Iwakura Substations were immersed in oil and sent by rail on low-floor railcars. However, to keep within the height limitations of the time, the laborious task had to be undertaken of removing half of the core upper yoke and then reattaching it onsite still immersed in oil. In 1935, a 154kV, 15MVA transformer for the Chosen Power Transmission Pyongyang Substation was transported using nitrogen instead of oil to reduce the weight, the first time such a method was employed. Special railcars for transporting transformers appeared in 1936 with the creation of the concave-style Shiki-60. Photo 3.16 shows freight being transported using the Shiki-60. In 1939, this railcar was used to transport a 154kV, 39MVA transformer for the Tokyo Electric Light Company Shinano River Power Station, packed in nitrogen using a temporary transport tank. This was recording-breaking pre-war rail transport.

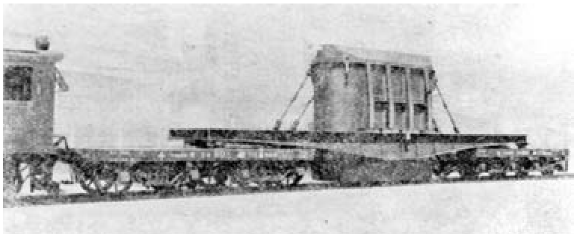


Photo 3.16. Assembled Transportation by the Special Shiki-60 Railcar

(7) On-Load Voltage Regulating Transformers

Another technology developed during this era was the on-load voltage regulating transformer. *__On-load tap changers__* were developed in the United States around the mid-1920s using a current limiting reactor to suppress crossflow while switching to the next tap. This was followed by the development in Germany of a method to suppress resistance. Various companies in Japan adopted the American reactor method, which was first used in 1930 in a 450kVA transformer for China Joint Electric (made by Shibaura)(9). The next couple of years saw a sudden flurry of progress and the creation of a 110kV, 12MVA transformer for Kumamoto Electric in 1931. Photo 3.17 shows a load voltage regulating transformer of the day, a three-phase, 6.3MVA transformer for the Kyoto Electric Light Nakamaizuru Substation. The first *__voltage phase__* *regulator* was installed at the Kansai Joint Power Amagasaki Power Station in 1933 to control power flow, with a regulating capacity of 9MVA and a line capacity of 88.5MVA. The German resistance method was introduced by Fuji Electric in 1935 and used in an 11kV, 3MVA, on-load tap-changing transformer for an electric furnace for Japan Nitrogenous Fertilizer.

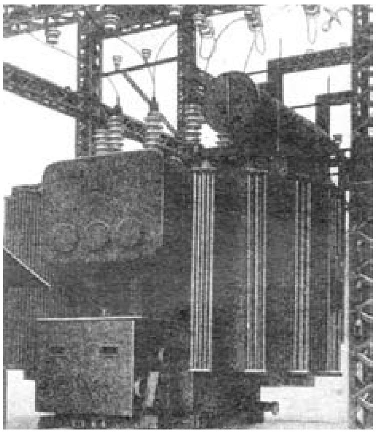
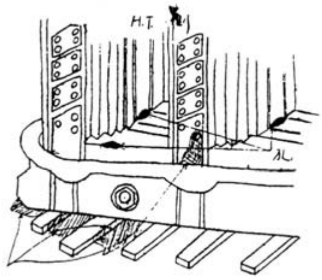


Photo 3.17. On-Load Voltage Regulating Transformer for the Kyoto Electric Light Nakamaizuru Substation (1932, made by Hitachi)

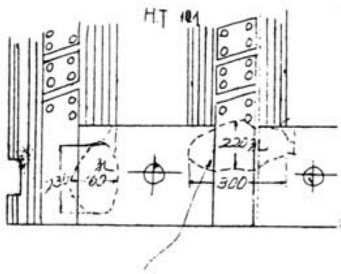
(8) Summary of the Early Showa Period and Melting of Transformer Cores

With the advent of the Showa Period, the Japanese transformer industry began to become self-reliant. This started with the 154kV transformer in the Nippon Electric Gifu Substation. The design of this transformer was difficult for the time, combining the features of existing American-made units to provide the capability to switch its low voltage 77/11kV. While it could be considered to be dependent on licenced technology, various separate designs resulted in it no longer using any of those technologies. Since this transformer worked well, most of the later 154kV transformers were produced domestically; this also led to the later boom on the Korean Peninsula.

However, we must not forget about the melting of transformer cores as well as the huge advances in Manchuria and on the Korean Peninsula. While there were fewer rail transport limitations than on the Japanese mainland, high capacity transformers went far beyond the scope of assembled transportation, so disassembled transportation was the norm. The cores at the time had 90˚ *alternately stacked joins*; factory and onsite production quality control was nowhere near comparable to what it is today. Damage to the core while running, inadequate drying onsite and faulty core sheets insulation led to increased loop electromotive force when forming each loop, as well as a high circulating current, causing melted cores. Many instances of melted cores, including outbreaks of fires, occurred from 1938 onwards among the high-capacity transformers supplied to Korea. This can be explained as transformer design and production technology not keeping up with the speed of capacity increase. Fig. 3.3 shows a sketch of core damage at the time, while Photo 3.18 shows an external view of a damaged 60MVA transformer.



The melted iron flows into this area at the same height as a 2” thick crossbar



Approximate volume of this area is 8,000cm^3

Fig. 3.3. Diagram of Melted Core

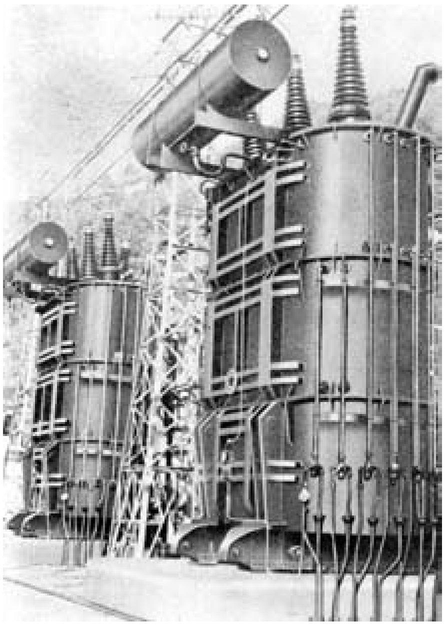


Photo 3.18. 60MVA Changjin River Transformer with a Melted Core (1938, made by Shibaura)

Lightning-protected design and impulse testing also appeared during this era. *Uniform insulation* was normal in Japan due to the different configuration. Although the *lightning-protected coil* structures developed in Europe could not be directly used in Japan at first, they were gradually introduced once their effect was validated. Japan also kept a watchful eye on impulse testing trends in the United States and other developed countries; it continued to prepare for standardisation and managed to issue standards during the Second World War, thereby laying a foundation for a fresh start after the war.

4. Breaking Away from Overseas Technology (Post-War Rebuild to 500kV Transformers)

4.1. Post-War Rebuild and the Achievement of Extremly-High Voltage Transformers

From the end of the 1930s and throughout the 1940s, domestic orders for new high-capacity transformers dropped off, with the main orders being to repair and restore the transformers that had been damaged during the war. Nevertheless, orders for new transformers began to trickle in from around 1948. A 22MVA transformer completed in 1949 for the Japan Electric Generation and Transmission Company's Ozone Substation was the first to undergo impulse testing following the issuance of JEC-110. This transformer had a newly-standardised partially shielded winding as its lightning-protected coil structure.

The advent of the 1950s brought special procurements for the Korean War and business quickly boomed again, accompanied by an increase in demand for electricity. A 275kV transformer for the Kansai Electric Power Company Shin-Hokuriku Trunk line started operating in 1952, the first in the post-war epoch(10). This was Japan's first domestically-produced extremely-high voltage transformer and it was also impulse-tested in accordance with the new standard. Four major companies were in charge of manufacturing. Hitachi oversaw 70MVA transformers(11) for the Narude Power Station, Mitsubishi 99MVA transformers(12) for the Hirakata Substation, Toshiba 99MVA transformers(13) for the Shin-Aimoto Substation and Fuji Electric 45MVA transformers(14) for the Tsubakihara Power Station.

This took much ingenuity, combining accumulated pre-war technology with new post-war technology.

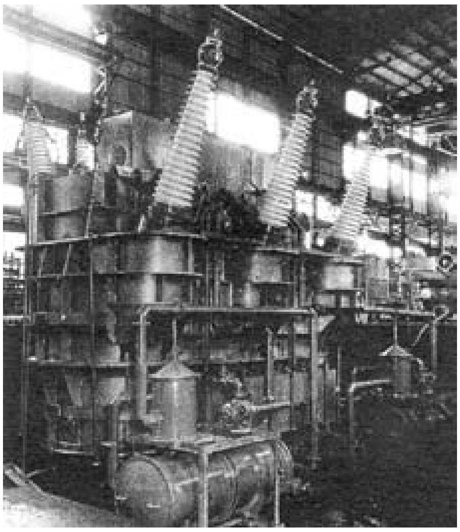


Photo 4.1. The First Domestically-Produced 275kV Transformer, Kansai Electric Power Company Narude Power Station (1951, made by Hitachi)

The 70MVA transformer made by Hitachi for the Narude Power Station (Photo 4.1) had a primary winding of 154kV, 50MVA, a secondary winding of 257kV, 70MVA and a tertiary winding of 11kV, 40MVA, with the EHV neutral point directly grounded. Accordingly, the ends of the EHV winding were positioned at the centre of the winding height and it was easy to insulate. This was the first structure in Japan to have a medium-voltage winding of 154kV; this was insulated together with the high-voltage winding using the _partially shielded winding_ method that had been developed in the 1940s.

The 99MVA transformer made by Mitsubishi for the Hirakata Substation (Photo 4.2) had a primary winding of 250kV, 90MVA, a secondary winding of 77kV, 99MVA and a tertiary winding of 10.5kV, 45MVA; this had an _equivalent capacitance_ of 117MVA, making it the highest capacity transformer ever. The primary neutral point was directly grounded. The primary winding was a *surge-proof winding*, which was becoming the norm for shell-type transformers. The tank also had a new *form-fit* design. Mitsubishi also built a 72.5MVA transformer for the Maruyama Power Station.

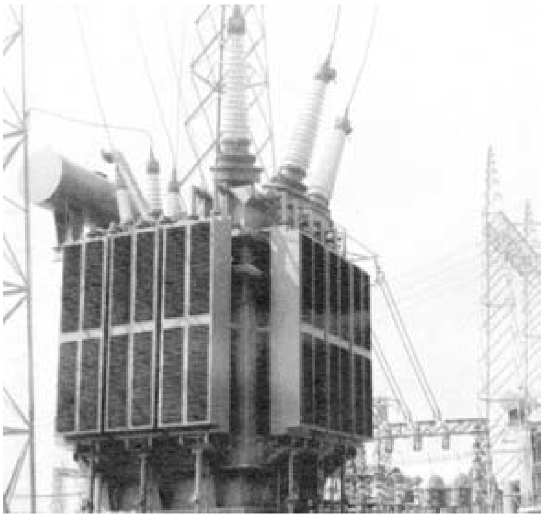


Photo 4.2. Japan's First 275kV Transformer, Kansai Electric Power Company Hirakata Substation (1951, made by Mitsubishi)

Toshiba's transformer for the Shin-Aimoto Substation had a primary winding of 275kV, 90MVA, a secondary winding of 166kV, 99MVA and a tertiary winding of 11kV, 45MVA, giving it the same equivalent capacitance as the Hirakata transformer, the highest capacity transformer ever. With the primary neutral point directly grounded, it was the first to have the *non-resonant transformer* structure developed by GE before the war. Another reason for this was that it was difficult to use a multiple cylindrical winding for the high voltage, as was commonly used in the West at the time, because it had a high medium-voltage winding of 166kV. Unlike the GE design, the stack shield for the non-resonant winding had some ingenious innovations. Besides the coil itself, it also had a system of connecting the insulation tube to the coil by means of a solid-insulation, electrostatic-capacitor electrode to prevent the coil from increasing in size. The medium-voltage 154kV winding was also a standard partially shielded winding. Fig. 4.1 shows a diagram of the winding structure.

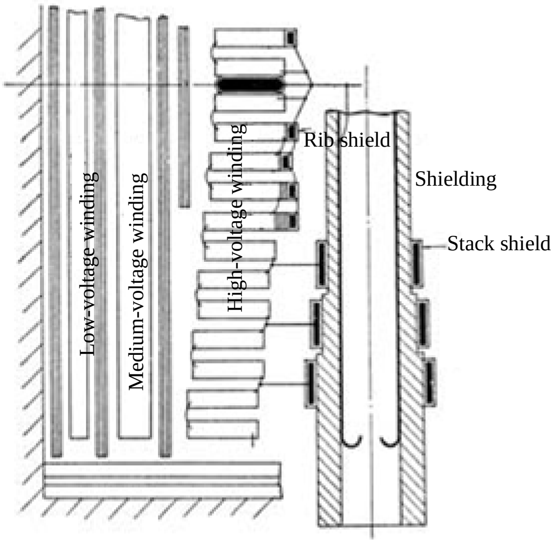


Fig. 4.1. Diagram of a Non-Resonant Transformer Winding Structure

Fuji Electric's 45MVA transformer for Tsubakihara Power Station also used a new structure. Since this one was for a power station and the high-voltage and low-voltage windings were opposite each other, a *non-resonant winding (multiple cylindrical winding)* developed by German company AEG was used. With the neutral points being directly grounded and the high-voltage neutral point and the low-voltage winding opposite each other, it was possible to minimise the main gap between the high and low voltage windings. This was the first use in Japan of a *main-gap-filling insulating structure* reportedly used in post-war Europe, reducing the size of the main gap and adapting well to the low-impedance specifications of the transformer.

Due to transportation constraints, all these transformers were disassembled for transport and reassembled/re-dried on site. Toshiba used some newly-developed core-erecting equipment for onsite assembly. Since the aim was to reduce the amount of lifting equipment on site as much as possible, assembling and erecting the core on top of the lower tank made it possible to make do with only a 25 ton crane on site. Meanwhile, Mitsubishi developed a new method of drying its form-fit tank structure by heating the tank through induction while also blowing hot air onto it.

4.2. The Revival of Technical Cooperation and the Increase in Proprietary Technology

Technical cooperation with overseas manufacturers revived once more in 1952, having been suspended during the war. This brought with it new technology that had been developed overseas during and after the war. Some of this technology was worked out and implemented purely from information such as literature, some was worked out through collaboration with overseas partners and information gained on observation tours of overseas factories, and some was developed overseas during the war. This new technology poured into Japan from the mid-1950s to the 1960s. To give a few examples, *vapour-phase-drying methods*, *frame-shaped cores*, coil forced cooling, *transposed cables* and many other technologies that are still used today were introduced at this time. *High series capacitance windings*, developed in 1950 in the United Kingdom, became the focus of independent investigation based on the UK information with the aim of making a proprietary product in 1951. *Main-gap-filling insulating structures*, used in Europe, underwent further development based on information from overseas; this technology was able to be implemented in 1951 and was also used in the first 275kV transformer, mentioned previously. Japan’s level of transformer technology capability grew considerably, with clarification on potential vibration, the knowledge that the impulse resistance of paper insulation is key to high series capacitance windings, the development of high air tight wire insulating paper, and *damper-shield windings* and other lightning-protected windings independently developed in Japan. Capacitor coupling shield windings, a later improvement on damper-shield windings, were even licenced to manufacturers in the United Kingdom, formerly a leader in transformer technology. The aforementioned transposed cables were also put to use in some equipment in 1957 based on information from overseas, which contributed greatly to their wider adoption later on.

The most impacting overseas technology introduced after the war was grain-oriented silicon steel sheets, developed by American company Armco in 1935. They were first used in 1955, imported from Armco. However, the full potential of the grain-oriented silicon steel sheets was not realised, as they were used with the *right-angled joins* of the existing core structure. It was not until 1956 that a frame-shaped core was used to make full use of the characteristics of the grain-oriented silicon steel sheets, in a 6MVA transformer for the Tokyo Electric Power Company Kichijoji Substation. Once Yawata Iron & Steel obtained a technology licence from Armco and began full-scale production in 1958, it began to increase in use. However, it was not until around 1962 that domestically-produced grain-oriented silicon steel sheets appear on the market and the Japanese transformer industry transitioned completely from the existing hot-rolled T-grade silicon steel sheets to frame-shaped cores made from cold-rolled G-grade grain-oriented silicon steel sheets. While the magnetic field strength used was initially 1.3T, not very different from the T-grade material, it grew to 1.6-1.7T from around 1962, which greatly contributed to increasing the capacity of the transformer through significant downsizing of the core.

4.3. High Capacity and Assembled Transportation become the Norm for Transformers

(1) High Capacity and Assembled Transportation of Substation Transformers

With an increasing demand for electricity in the 1950s, primary substation transformer capacity was increased to 30-60MVA; to make it quicker and easier to install these high-capacity transformers on site, it became normal for them to be transported assembled using special freight cars. Much ingenuity was devoted to that purpose.

It started in 1951 with the adoption of *form-fit tank* at the shell-type transformer. A 45MVA transformer for the Kyushu Electric Chikujo Power Station was *transported, fully assembled, sideways* using the Shiki 100. The low-floor Shiki 120 was brought out the following year in 1952, and used to transport a 65MVA transformer for Chikujo the same way on its side. A 39MVA transformer for the Tokyo Electric Power Company Higashi-Chiba Substation was transported on its side with a form-fit tank. In 1954, a 66MVA transformer for the Tokyo Electric Power Company Keihoku Substation was transported using Japan's first Schnabel railcar, the Shiki 140 (Photo 4.3).

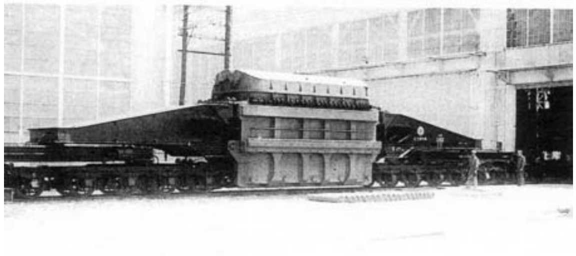


Photo 4.3. A 66MVA Transformer for the Tokyo Electric Power Company Keihoku Substation Transported by the Shiki 140 Schnabel Car (1954, made by Hitachi)

A special three phase system was developed in 1955 and used on a 275kV, 93MVA transformer for the Electric Power Development Company Sakuma Power Station (Photo 4.4).

Photo 4.4. The First Special Three Phase Transformer, a 93MVA Transformer for the Electric Power Development Company Sakuma Power Station (1955, made by Mitsubishi)

The same year, a three-phase, five-limb core was used in a 99MVA transformer for the Chubu Electric Power Company Higashi-Nagoya Substation. This was transported assembled using the Shiki 170 Schnabel car. Photo 4.5 shows the core and coils of this transformer.

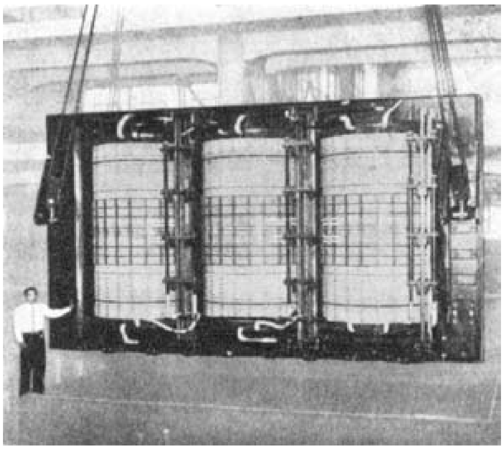


Photo 4.5. A 99MVA Transformer for the Chubu Electric Power Company Higashi-Nagoya Substation, the First to Use a Five-Leg Core (1955, made by Toshiba)

Successively larger Schnabel cars were produced from 1957 to 1959 and freight transport capacity continued to improve. Transportation of high-capacity transformers progressed, with the transportation a 180MVA transformer for the Kyushu Electric Power Company Nishitani Substation in 1958, a 275kV, 264MVA transformer for the Electric Power Development Company Nishi-Tokyo Substation in 1959, and a 262.5kV, 300MVA transformer for the Chubu Electric Power Company Nishi-Nagoya Substation in 1963 (Photo 4.6).

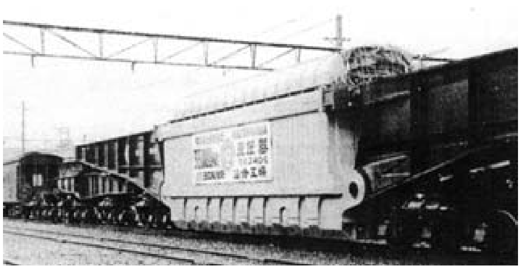


Photo 4.6. A 300MVA Transformer for the Chubu Electric Power Company Nishi-Nagoya Substation, the Highest Capacity Transformer to be Transported (1963, made by Hitachi)

Fig. 4.2 shows the post-war advances in the capacity of assembled-for-transport transformers for substations. This was undergirded by the introduction of the Schnabel car to make the most effective use of rail transport limitations, the downsizing of the core through the use of grain-oriented silicon steel sheets and the adoption of the five-leg core structure. The use of graded insulation on the 154kV neutral point under JEC-120 issued in 1952 and significant improvements to the winding coil space factor due to lightning-protected winding structures also greatly contributed to this improvement.

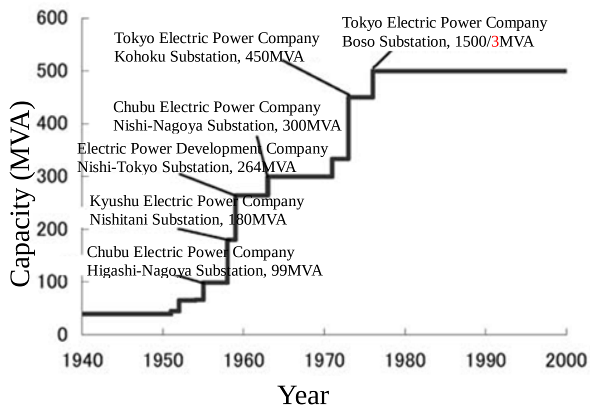


Fig. 4.2. Advances in the Capacity of Assembled-for-Transport Transformers for Substations

Sea transport was also used. In 1956, a 160MVA transformer for the Tokyo Electric Power Company Chiba Power Station was shipped with the use of a floating crane (Photo 4.7). With the later increase in single-unit capacity of transformers for thermal power stations, it became possible to transport assembled three-phase transformers.

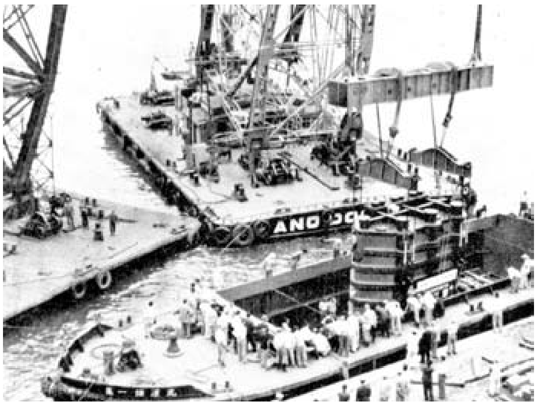


Photo 4.7. A 160MVA Transformer for the Tokyo Electric Power Company Chiba Power Station Shipped with the Use of a Floating Crane (1956)

Meanwhile, there was a growing demand for distribution transformers to be able to be transported whole by trailer, particularly in urban areas. This started with a 66kV, 10MVA transformer in 1958. At the same time, vehicle-movable transformers were also introduced; these could be moved in emergency situations.

(2) Increased Capacity of Power Station Transformers

The pace at which power station transformers increased in capacity is surprising.

While many thermal power stations used imported machines for their primary turbines and generators, they were using domestically-produced equipment rather than imported equipment for their primary transformers, since even before the war Japan had reached a world-record level of technology in this area. One such pre-war record product was a 63MVA transformer at the Chubu Electric Power Company Meiko Thermal Power Station, while an 85MVA transformer was completed in 1955 for the Chubu Electric Power Company Mie Thermal Power Station and a 160MVA transformer was completed in 1956 for the Tokyo Electric Power Company Chiba Thermal Power Station. The capacity record continued to be broken again each year, with a 200MVA transformer for the Chiba Thermal Power Station in 1958, a 270MVA transformer for the Chubu Electric Power Company Shin-Nagoya Thermal Power Station in 1959 and a 300MVA transformer for the Tokyo Electric Power Company Yokosuka Thermal Power Station in 1960. The progress in power station transformer capacity is shown in Fig. 4.3.

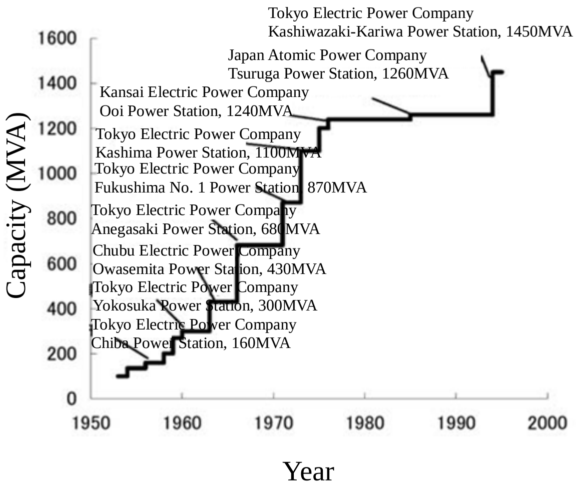


Fig. 4.3. Progress in Power Station Transformer Capacity

Meanwhile, large-scale hydroelectric dams were being built, requiring high capacity transformers for hydroelectric power stations. However, since hydroelectric power stations often present major constraints on rail or road transport, a method was developed in 1955 of transporting each of the three phases separately; this method later became common. Examples include a 93MVA transformer for the Electric Power Development Company Sakuma Power Station (Photo 4.4)[15] and a 133MVA transformer for the Electric Power Development Company Okutadami Power Station, completed in 1959[16]. However, in many cases, they could not meet the size or weight specifications for transport and were still disassembled for transport, such as a 95MVA transformer for the Kansai Electric Power Company Kurobegawa No. 4 Power Station completed in 1960. The system of disassembly for transportation gradually declined following the appearance of the 500kV transformer and the emphasis on transformer reliability in the 1970s.

4.4. Accessories and On-Load Tap-Changing Transformers

(1) Cooling Systems and Conservators

Let us now examine transformer accessories. In terms of cooling systems, water cooling was the main system used in pre-war Japan. These were superseded by forced-oil cooling systems that had long been common in Europe. The issue of coolant preservation in substation transformers had a major influence on this change. A 66MVA transformer for the Tokyo Electric Power Company Wadabori Substation completed in 1951 (Photo 4.8) was simplified to have the cooler mounted directly onto the body of the transformer; nowadays it is commonplace to have a unit cooler cooling system with a cooler and pump combined. *Conservators* have a *nitrogen-filled tank* system[17]. While nitrogen-filled tank system conservators were first used in 1942, at that time they were not widely used for economic reasons. After the war, they were more widely adopted in recognition of their effectiveness in conserving oil. While the *three-chamber* structure was common at the time, A 66MVA transformer comprised a *floating tank*, which was the standard structure until the transition to the *diaphragm structure* in the 1960s. The diaphragm structure was also licenced technology, from American company GE. The first transformer to apply this technology was in 1960, with a 100MVA transformer for the Tokyo Electric Power Company Chiyoda Substation, the first high-capacity underground substation, using imported rubber pouches. With rubber diaphragms later being domestically manufactured, these superseded the nitrogen-filled tank system by around the mid-1960s.

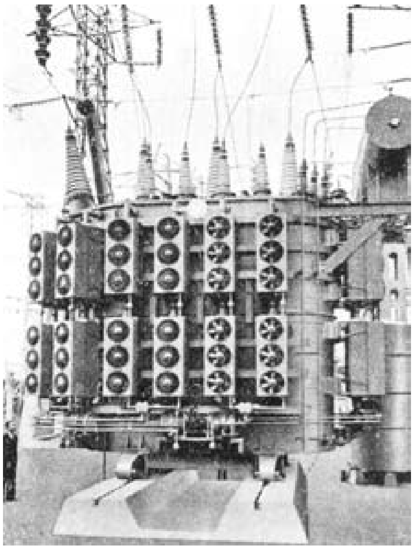


Fig. 4.8. A 66MVA Transformer for the Tokyo Electric Power Company Wadabori Substation, the First to Use a Unit Cooler (1951, made by Toshiba)

(2) On-Load Tap-Changing Transformers

Another technological advance during this era was the popularisation of on-load tap-changing transformers to provide a constant voltage supply to boost the quality of the electricity available. The on-load tap changers at this time were mainly American-style reactor-type LTCs, while some were the German/Janssen-style resistor-type LTCs. Some transformers had a load voltage regulator (LVR) connected in series to the main transformer, while some were load ratio control transformers (LRT), with a tap winding inside the transformer itself. At the time, these were mainly used for electricity distribution. However, in the late 1950s, on-load voltage regulation began to be carried out by high-capacity transformers at primary substations. The two methods used were LVR and

LRT; examples using LVR include a 90MVA transformer (LVR: 220kV±10, ±j30kV) for the Kyushu Electric Power Company Yamaie Substation in 1956 and an 80MVA transformer (LVR: 77kV±5%) for the Hokuriku Electric Power Company Fushiki Substation in 1957. Examples using the LRT system include a 66MVA transformer for the Chugoku Electric Power Company Tokuyama Substation in 1957 and a 75MVA transformer for the Tokyo Electric Power Company Kuramae Substation in 1959, using an embedded LRT.

The 1960s saw a greater trend towards using LTCs in primary substation transformers, while on-load tap changers were being built into transformer tanks. There was an increasing demand from power companies for LRTs that could be transported assembled, like the transformers themselves. There was also a growing demand to use highly practical LTCs with longer lifespans and fewer maintenance requirements. German company MR received worldwide attention at the time as being the most suited to meeting these demands. In 1963, three Japanese transformer manufacturers entered into technical cooperation with MR and after that models developed by MR became the main ones used in Japan, a trend which continues to the present day. Photo 4.9 shows a 300MVA transformer for the Tokyo Electric Power Company Kita-Tokyo Substation, the first to have a built-in MR LTC, while Photo 4.10 shows the LTC itself[18].

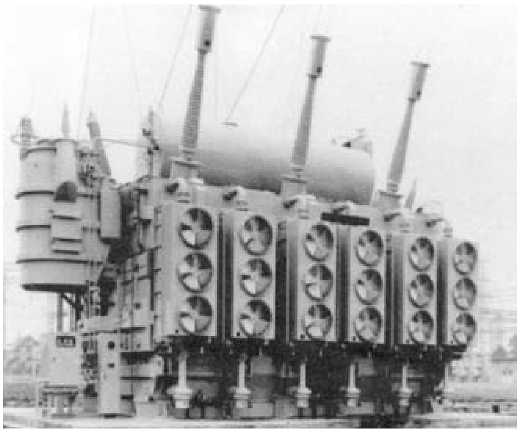


Photo 4.9. A 300MVA Transformer for the Tokyo Electric Power Company Kita-Tokyo Substation, the First to Have a Built-in MR Resistor-Type Tap-Changer (1962, made by Mitsubishi)

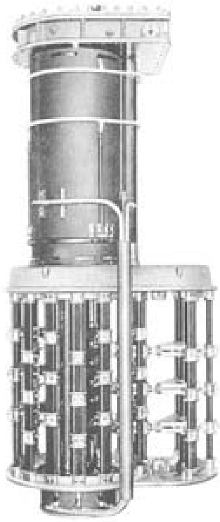


Photo 4.10. F-Type Tap-Changer by MR

4.5. Elephant Bushing

To meet the increasing demand for electricity, a 66-154kV system was directly introduced to urban centres through cables, sometimes directly connected to transformers by means of underground substations. Underground hydroelectric power stations were planned, with the generated voltage stepped up by underground transformers; in some instances, the electricity was transmitted underground by means of oil-insulated cables. In such cases, it was usual to have the cable end terminal connected to a transformer bushing by means of overhead wires. Meanwhile, by around the mid-1940s it was becoming increasingly common in the West to connect the cable to the transformer in oil. In 1958, a 66kV transformer became the first in Japan to be connected in oil; in 1960, an oil connection with a so-called *elephant bushing* was used to connect 154kV to a 100MVA transformer for the Tokyo Electric Power Company Chiyoda Substation, the first high-capacity underground urban substation, and 275kV on a 133MVA transformer (Photo 4.11) for the Electric Power Development Company Okutadami Power Station, an underground power station(16). For the purposes of clarifying differences in onsite assembly time and load sharing, the elephant bushing structure mainly used in Japan has the cable head connected to the transformer in a connection duct using an oil-oil bushing. In this case, the length of the bushing pocket and connection duct must be made as short as possible to reduce the amount of space used in the underground substation. The bushings used at the time transitioned from the oil bushings with insulation tube barriers, predominant since before the war, to *oil-impregnated paper condenser bushings*. *Resin (dry) condenser bushings* developed in Europe were smaller in size yet still effective, so this system began to be adopted through technology imports. However, the dry condenser bushings did not use a vacuum infusion for the resin, so some tiny voids remained. Later testing that showed that this was prone to partial discharge, which was difficult to distinguish from partial discharge from the transformer itself. This was reported along with the fact that the operating voltage would drop in quality after extended use; around the mid-1970s, this was replaced by the vacuum infusion method. However, around that time, the resin spacer developed by GIS began to be used for their compactness. After that, various types of bushings were used in various combinations.

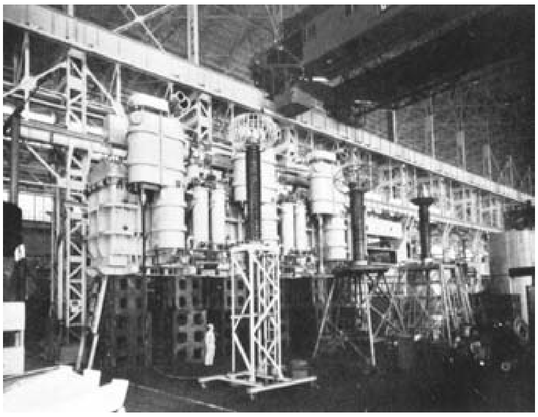


Photo 4.1. A 275kV Direct-Cable-Coupled Transformer
133MVA Transformer for the Electric Power Development Company Okutadami Power Station (1960, made by Toshiba)

4.6. The Appearance of Ultra-High Capacity Transformers

(1) The Appearance of Ultra-High Capacity Transformers

The advent of the 1960s saw a sudden boom in demand for electricity as Japan entered a period of rapid economic growth. While single-unit capacity expanded at a rapid pace from the perspective of capital investment efficiency, the speed at which thermal power station transformers expanded was amazing. Fig. 4.3 shows the progress of transformer capacity in Japan; this figure shows a sudden climb from the 1960s to the early 1970s.

The completion of a 300MVA transformer for the Tokyo Electric Power Company Yokosuka Power Station in 1960 was followed by the successive completion of a 370MVA transformer for the Kansai Electric Power Company Himeji No. 2

Power Station, a 420MVA transformer for the Tokyo Electric Power Company Yokosuka Power Station and a 430MVA transformer for the Chubu Electric Power Company Owasemita Power Station in 1963, and the completion of a 680MVA transformer for the Tokyo Electric Power Company Anegasaki Power Station in 1966 (Fig. 4.12)[19]. Following the provision in 1964 of a 100MVA transformer to the Japan Atomic Power Company Tokai Nuclear Power Station – Japan's first nuclear power station – a 490MVA transformer was completed for the Tokyo Electric Power Company Fukushima No. 1 Nuclear Power Station in 1969, with an 870MVA transformer provided to the same power station as a secondary transformer in 1971.

In 1973, a 1100MVA transformer supplied to the Tokyo Electric Power Company Kashima Thermal Power Station became the first transformer to exceed 1000MVA (Photo 4.13)[20]. A 680MVA transformer and an 1100MVA transformer were completed for the Tokyo Electric Power Company Sodegaura Power Station as 500kV transformers to step up the power supply directly at the power station to feed into a 500kV network that had also commenced operation in 1973.

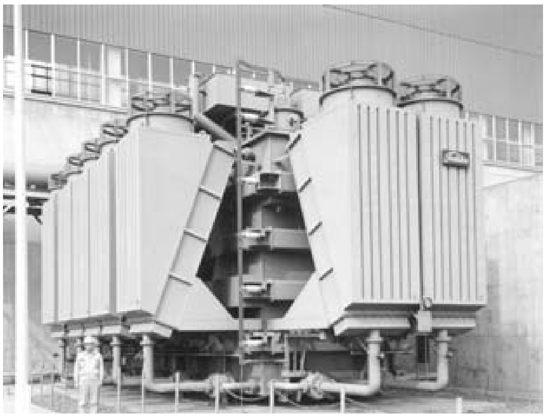


Photo 4.12. A 680MVA Transformer for the Tokyo Electric Power Company Anegasaki Power Station (1966, made by Toshiba)

Photo 4.13. An 1100MVA Transformer for the Tokyo Electric Power Company Kashima Power Station (1973, made by Toshiba)

Since this pace of capacity increase was around the same as that found in the United States and various other countries, Japan could no longer take the step of introducing technology developed or established overseas before establishing its own technology as it had done in the past with high voltage; it had to try to solve the issues that accompanied high capacity on its own.

As well as high capacity, there were increasing demands for transformers to have higher impedance of around 1.5 times the existing specifications to limit the short-circuit capacity of the networks. Consequently, one of the most significant issues with high-capacity transformers was that of cyclic currents within the structure due to leakage flux in the windings and the loss and heat caused by these currents.

(2) Dealing with Leakage Flux

Windings started to counteract leakage flux in 1958 with *multiple cylindrical windings*, which had improved insulation and better production conditions, as well as the widespread use of *transposed cables* as the conductor within these windings. Transposed cables have two lengths of thin conducting material twisted at a pitch of around 10cm, making them very strong mechanically. They also effectively halve the fringing flux at the ends of the winding and are still widely used today.

The greatest difficulty in counteracting leakage flux is preventing selective heating of the tank. Cyclic currents are generated in the tank not only due to leakage flux from the winding, but also due to the magnetic field of the high current lead wire. *Magnetic tank shields* were used to deal with this in shell-type transformers from 1952 onwards, while core-type transformers used aluminium *electromagnetic shields* from 1958. However, there were issues with the structure and scope of mounting these; these issues were eventually solved through repeated trial and error on several products. Selective heating from cyclic currents flowing within the inner structure of the tank due to leakage flux or the magnetic field of the high current lead wire made things difficult, as this could not be immediately detected externally. In many cases, the issue appeared and was dealt with on site. Gas-in-oil analyses are commonly used these days to detect selective heating; this technology is the result of these early processes. As mentioned previously, the conservator system used in Japan from the 1960s onwards was the diaphragm system. Japan had very high analytical precision in detecting even the tiniest amount of dissolved gas in oil, meaning it could make its evaluation criteria very strict regarding flammable gas generated by overheated oil, which contributed greatly to eliminating the causes of flammable gas generation. Determining the presence or absence of selective heating began in the late 1960s, with gas-in-oil analyses during temperature rise tests at factories.

Thus, from the late 1960s to the 1970s, various countermeasures were adopted, such as the use of a slit structure for core tie plate, the use of magnetic shielding for core clamp, the use of *double concentric winding arrangements*, the introduction of cyclic current reduction or preventive measures, such as preventing multi-point grounding or using insulation, the use of structures to prevent incomplete contact, the use of tank magnetic shields (for core-type transformers), the development of low-voltage high current bushing, and measures to prevent overheating of the connection between the low-voltage isolated phase bus and the low-voltage bushing pocket. Into the 1980s, it became more common to use a computer to analyse the electromagnetic field; this increased accuracy went a great way to solving the leakage flux issue; however, since transformers are complex in shape they are generally difficult to analyse. Even today, some aspects of this issue have not been fully resolved.

The pace of transformer capacity increase later slackened off. Nuclear power stations placed orders for transformers, with a 1200MVA transformer for the Japan Atomic Power Company Tokai Nuclear Power Station in 1975, a 1240MVA transformer for the Kansai Electric Power Company Ooi Nuclear Power Station in 1976, a 1260MVA transformer for the Japan Atomic Power Company Tsuruga Nuclear Power Station in 1985 and a 1450MVA transformer for the Tokyo Electric Power Company Kashiwazaki-Kariwa Nuclear Power Plant in 1994 (Photo 4.14)[21]. More recently, a 1510MVA transformer was completed for the Chubu Electric Power Company Hamaoka Nuclear Power Plant in 2002 (Photo 4.15)[22], the current world record holder for the highest capacity transformer in the world.

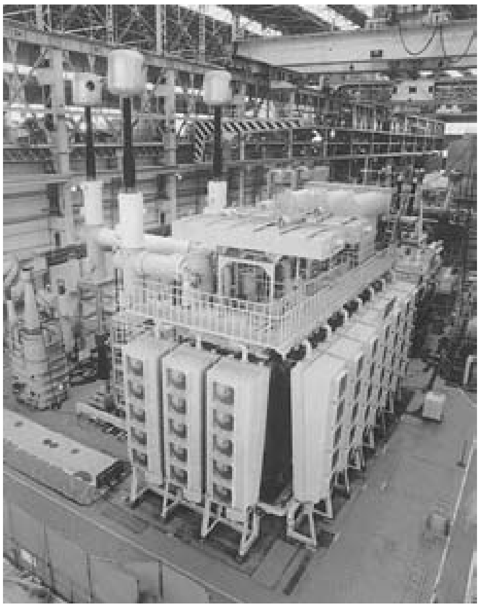


Photo 4.14. A 500kV, 1450MVA Transformer for the Tokyo Electric Power Company Kashiwazaki-Kariwa Nuclear Power Plant (1994, made by Hitachi)

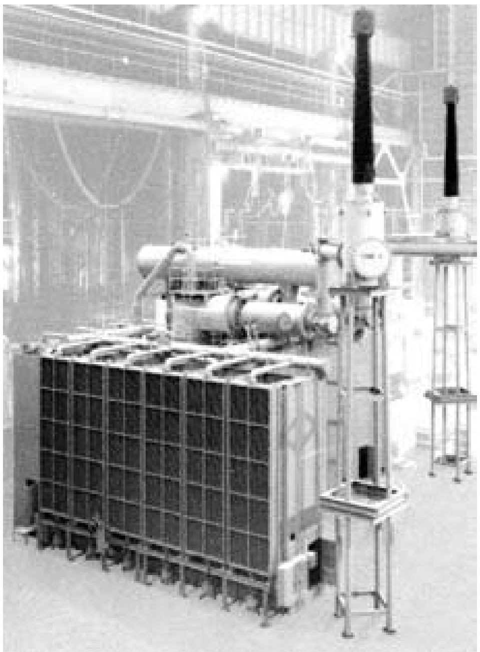


Photo 4.15. A 500kV, 1510MVA Transformer for the Chubu Electric Power Company Hamaoka Nuclear Power Plant (2002, made by Mitsubishi)

4.7. Transformer Exports and the Development of 500kV Transformers

(1) Post-War Transformer Exports

Post-war transformer exports were often based on international yen loans. At first, these were aimed at India and Taiwan, until around 1960. At this point, research and development began on the next level of supply voltage: the idea of the 400kV power supply such as was implemented in Europe and other areas. Based on these developments, Japan succeeded in securing an order for a 330kV transformer for Australia in 1960, followed by orders for 330kV, 160MVA and 100MVA transformers in 1961. These orders were sent by Hitachi and Toshiba. Photo 4.16 shows the exterior of the 330kV, 100MVA transformer. This could be said to be the beginning of Japan's official transformer exports. These transformers were also Japan's first on-load tap-changing *auto-transformers*, with the tap changing at the end of the medium-voltage 132kV line. The windings incorporated the latest technology, being both the newly-developed damper-shield windings as well as high series capacitance windings[(23)(24)]. This was a time of adopting new technology, including the use of thermal upgraded insulating paper, the use of crêpe paper and flexible copper twist wire for the lead, and crimped lead terminals.

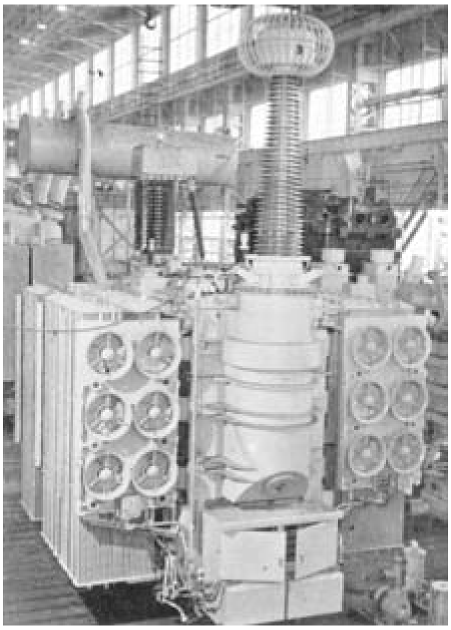


Photo 4.16. A 330kV, 100MVA, On-Load Tap Changing, Auto-Transformer for Australia (1961, made by Toshiba)

(2) Initiatives towards 500kV Transformers and 500kV Transformers for Export

Japan's decision in the 1960s to move up to 500kV, the next level of supply voltage, spurred on development. By 1963, development was fully underway, with the creation of full-scale models with the assumption that these would be transported by rail. By 1966, Hitachi, Toshiba and Mitsubishi had sent 500kV, 10MVA prototypes to the Takeyama Ultra High Voltage Laboratory for demonstration testing (Photo 4.17)[25]. Further, since the aim was to build up experience overseas before applying the technology in Japan, by 1965 each company had successfully secured orders for high-capacity 500kV transformers from Canada, followed by the United States and Australia, as well as orders from Mexico for 400kV transformers. Photo 4.18 shows the inside of Japan's first 500kV transformer, a 100MVA transformer bound for Canada. As a result of a series of insulation faults not long after putting US-made 500kV transformers into operation early in the 500kV stage, these transformers were distinctive in that the specifications required partial discharge testing in addition to the existing insulation tests.

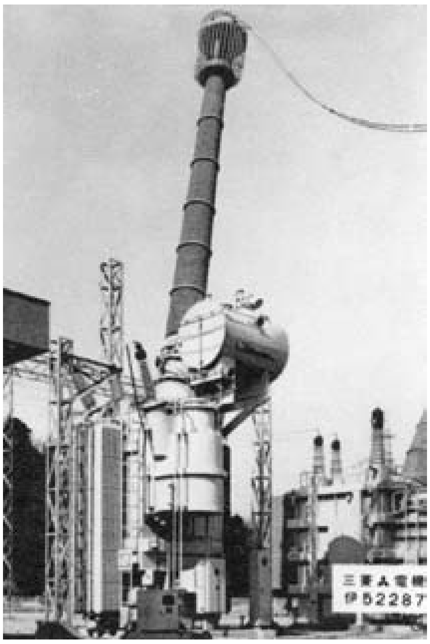


Photo 4.17. A 500kV, 10MVA Transformer Used for Voltage Impression Testing
Central Research Institute of Electric Power Industry Yokosuka Research Institute (1966, made by Mitsubishi)

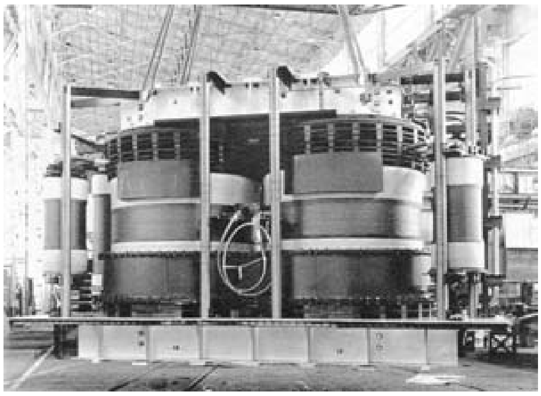


Photo 4.18. Core and coil of Japan's First 500kV Transformer, a 100MVA Transformer Bound for Canada (1967, made by Toshiba)

(3) Initiatives towards Partial Discharge Testing

In those days, design/production and testing to prevent partial discharge was completely by trial and error. Tentative measures were taken, such as eliminating concentrated electric fields from the electrodes, testing and improving the insulating materials used, increasing awareness of dust-proofing by painting the inner structures in light colours, introducing new insulating technology, and improving the production environment through the introduction of cleanrooms and low-humidity working chambers. While these were successful to some extent, it was rare to pass a test the first time around and the interior of the transformer was repeatedly cleaned with transformer oil to remove foreign bodies. Various other countermeasures were later adopted, such as the use of voidless insulating materials, the removal of metallic contaminants from the insulation, the introduction of insulation moisture control, and controls to prevent the enter of foreign bodies. While *acoustic corona location* technology became established, as well as technology that identified the point of corona discharge, this was not enough to radically solve the issue of partial discharge(26). This was issue completely solved from the mid to late 1970s onwards when 500kV transformers were launched in Japan, thanks to an understanding of partial discharge inception field strength in oil, configuration and management of allowable electric field values, outfitting of dust-proof machine rooms, complete awareness of dust protection among workers and a lot of Japanese-style quality control. It took nearly ten years to completely solve this issue. Nowadays, it is standard practice in Japan to use partial discharge testing to ensure no internal partial discharge. This guarantees the reliability of the insulation of the transformer. While criteria such as IEC standards are more relaxed elsewhere than in Japan, this cannot be said to be unrelated to the fact that there is a clear difference between the work environment and workers' ethic in Japan and that in other countries.

4.8. Completion of Domestic 500kV Transformers and Flow Electrification Incidents

(1) Development of 500kV Transformers for the Domestic Market

In 1970, Tokyo Electric Power Company finally decided to go to 500kV transmission and decisions got underway on transformer specifications. While some specifications had been adopted for an interconnected grid between Kansai Electric Power Company and Chugoku Electric Power Company, most transformers in Japan were almost first application of *auto-transformer* type with a capacity bank of 1000MVA. While many of the tap changers were positioned on the medium-voltage terminal on a auto-transformer, as often done overseas, there was little precedent for this on 275kV, many transformer faults had occurred in the LTC and there were reliability issues with using them with a voltage as high as 275kV. Accordingly, the neutral switch method was adopted, despite the fact that this means larger equipment due to tap core excitation, the fact that this would make the tap step voltage uneven and other shortcomings. Moreover, the tap winding was placed separately as the on-load voltage regulator, enabling the main transformer to be moved independently in the event of failure near the LTC.

Lightning impulse test voltage was set at 1550kV, a step lower than the 1675kV used in lightning impulse testing on 500kV transformers in the West at the time. Switching impulse testing was also adopted at first, with a test voltage set at 1175kV. While in the West it was usual to determine the AC test voltage in way that linked to the lightning impulse test voltage, but based on 275kV running results in Japan, it was set at 840kV, quite high compared to that used in the West. Decisions on partial discharge testing were carried out with reference to overseas precedents, with a test pattern determined of 1.5E (E: normal operating voltage) 1 hour, 2E 5 minutes, 1.5E 1 hour. AC testing was determined while carrying out testing on prior testing equipment. Thus, 500kV transformers in Japan were based on the running results of 275kV transformers; specifications were set in order to improve reliability, forming the start of the later reliability-centred principle that continued until the 1990s. Kansai Electric Power Company, which followed Tokyo Electric Power Company in commencing 500kV transmission, set its AC test voltage at 680kV, having linked it to lightning impulse testing as in the West; however, it ultimately set it at an intermediate 750kV during later test voltage standardisation.

(2) Completion of 500kV Transformers

The first 500kV transformers in Japan were supplied to the Tokyo Electric Power Company Shin-Koga and Boso Substations in 1971 by Toshiba and Mitsubishi, with three banks each[27][28]. Photo 4.19 shows the exterior of a 500kV transformer for the Shin-Koga Substation, while Photo 4.20 shows the interior of the same. Around 1972, during testing prior to commencing operation, there were two successive insulation breakdowns at the Boso Substation. Once these were investigated and repair, 500kV transmission commenced in Japan in 1973.

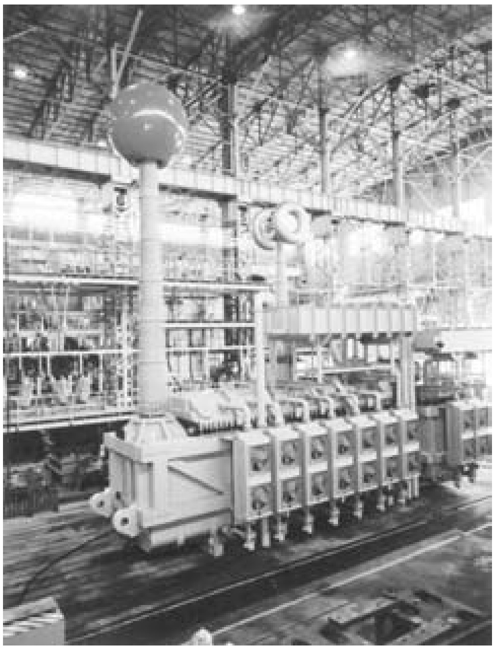


Photo 4.19. The First Domestic 500kV Transformer A 1000/3MVA Transformer for the Tokyo Electric Power Company Shin-Koga Substation (1971, made by Toshiba)

Photo 4.20. Core and Coil of the Shin-Koga Substation 1000/3MVA Transformer

These 500kV transformers essentially comprised the windings and insulation structured used successfully in the 500kV transformers for export.

However, a more compact design was required, given the different rail transport limitations and due to the high AC test voltage values, the heavy use of barrier insulation arranged alternately between oil gaps and the insulating material was adopted. Further, while dust protection was being reinforced with the building or relocating to new factories, dust protection was not thoroughly enforced and workers had little awareness of this issue, so it was rare to pass partial discharge testing the first time around.

A auto-transformer built in 1974 for Kansai Electric Power Company had the tap winding built into the main transformer, with the tap winding wound around the side leg of the single-phase core. While power companies had differing views on reliability, even Tokyo Electric Power Company adopted the system of winding the tap winding into the main body of the transformer for its 500kV and 154kV system transformers, rather than the LVR system. There was a difference in importance between the 154kV and 275kV networks.

In 1974, transformers were first used to directly step up to 500kV from the generators at the Tokyo Electric Power Company Sodegaura Power Station and the Kansai Electric Power Company Okutataragi Pumped Storage Power Station.

(3) 500kV Transformer Accidents and Flow Electrification

During testing at the Boso Substation in 1972, two transformers in succession experienced insulation breakdown, as mentioned earlier. An investigation was launched on all the transformers from the factory, including the two that had broken down, but no clear cause was found at the time. It was concluded that the insulation breakdown was probably caused by increased moisture content in the insulation, since the transformer oil infused in the insulation had leaked out when exchanging the transportation cover for the main cover on site, making it susceptible to water absorption. However, during prolonged voltage impression at the factory, one of the transformers emitted a sound from within that coincided with the electrical signal. As light from electrical discharge could be confirmed from the testing observation window, it was concluded that electrical discharge was taking place inside the transformer. It was also concluded that this was due to static shock from the oil flow, since the discharge varied with the operation of the pump. The oil industry had experienced issues such as tanker explosions and pipeline fires from static electricity, but nobody at the time expected oil flow to cause electrostatic discharge inside an insulation-oriented machine such as a transformer to the point of insulation breakdown. Tracing the cause of this meant re-investigating static electricity from the ground up. In 1974, soon after research on flow electrification started, another insulation breakdown occurred during voltage impression testing on a transformer for the Shin-Tokorozawa Substation. This time, too, there was a lot of damage inside the transformer so the cause could not be determined, but when another insulation breakdown occurred on a second transformer during subsequent voltage impression testing, the possibility of electrostatic discharge was considered. A detailed examination of the intact coils of the three arranged in parallel with the legs showed tracking in the insulation, probably due to a lot of electrostatic discharge in the oil flow channel in the lower part of the coil. It was determined that the insulation breakdown in this transformer was from electrostatic discharge developing into AC flashover. Right before this incident, electrostatic discharge had successfully been induced in a simulated cylindrical coil inlet on a cylindrical full-scale model. By comparison with this, it was determined that electrostatic discharge was the cause of this incident. Fig. 4.4 shows the site of occurrence of tracking marks from electrostatic discharge. Photos 4.21 to 4.23 show example tracking marks.

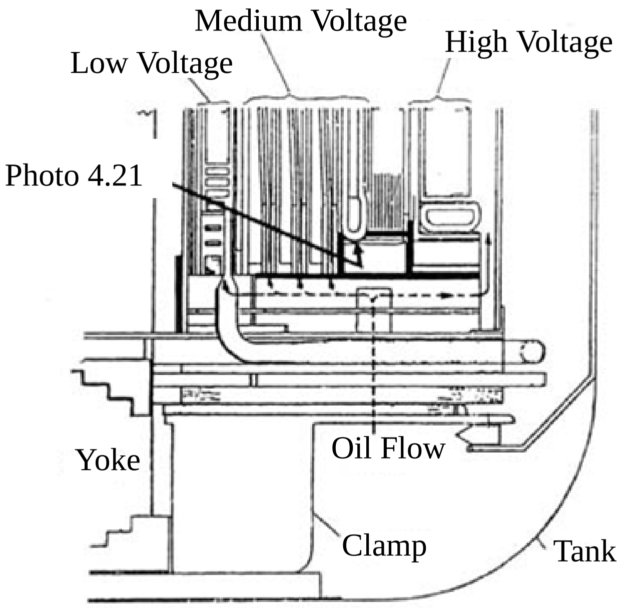


Fig. 4.4. Site of Occurrence of Electrostatic Discharge Marks

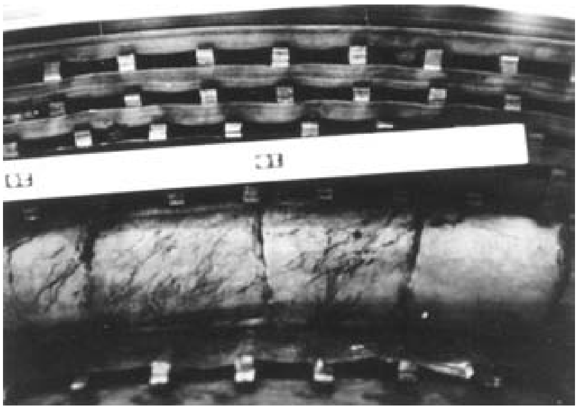


Photo 4.21. Electrostatic Discharge Marks (Medium-Voltage Multiple Cylindrical Winding Terminal Shield)

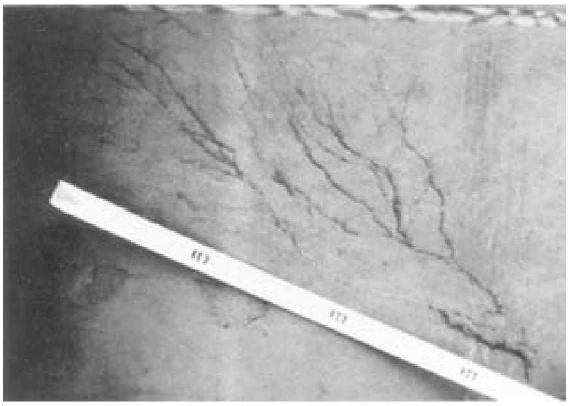


Photo 4.22. Ibid. Tertiary Winding Basic Insulation Cylinder Inner Side View

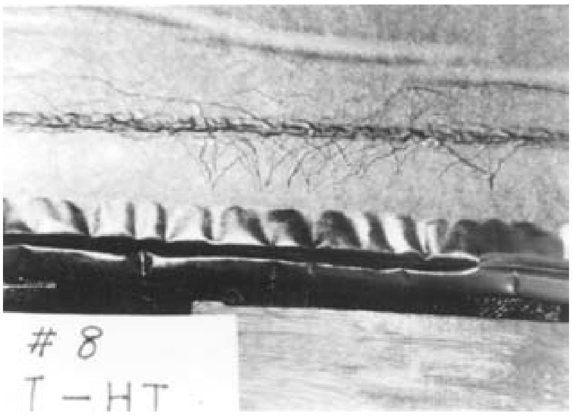


Photo 4.23. Ibid. High-Voltage Winding Basic Insulation Cylinder Inner Side View

5. Development of Independent Technology (Overcoming Flow Electrification and the Challenge of New Technology)

5.1. Overcoming Flow Electrification and Back-to-Basics Development[(29)(30)(31)]

(1) Investigating the Causes of Flow Electrification Incidents

To determine the cause of this incident, manufacturers changed all kinds of conditions using actual transformers, full-scale models and basic models. This confirmed that the susceptibility of transformer oil to electrification, the shape of the oil channel, the local flow velocity, the AC electric field and the surface state and moisture content of the insulation all have an electrostatic discharge causative effect. Different transformer oils varied in the degree of electrification of the oil; it was later confirmed that there were variances in time. While it is still not known what substance causes this timewise variation, the electrification is thought to vary dramatically due to trace substances in the oil being activated by dissolved oxygen and copper ions in the oil. Consequently, differences in the time between oiling and voltage impression is thought to result in differences between transformers in the degree of electrification and whether or not electrostatic discharge will occur. As a result of a flurry of research by various companies, countermeasures against flow electrification were established in 1976. The results of this study were also introduced overseas[(32)(33)(34)(35)], but received little attention at the time. However, in the 1980s, various places around the world reported trouble thought to be from electrostatic discharge. It started to receive more attention and continues to be a major issue even today. Even after countermeasures against flow electrification were established, research continued on the degree of electrification of transformer oil and on agents to control it. Since transformer oil is refined from petroleum oil, it is a mixture of various chemical compositions and it remains impossible to identify the trace components leading to the degree of electrification. Still, experimental results show that changes in the electrification of transformer oil can be controlled if benzotriazole (BTA) is added to it at an amount of 10ppm. This practice of adding BTA to transformer oil has been commonly adopted in Japan since the 1980s; the transformer oil standards also include an appendix on BTA-added oil.

(2) Reflecting on Flow Electrification Incidents and Later Developments

At the time, it was impossible to predict this flow electrification phenomenon. In terms of incorporating oil into the coil, the designs at the time only gave thought to the cooling of the coil and overlooked the oil flow. Problems occurred in areas with high local flow velocity. For one thing, this led to a reflection on the underlying idea that parts designed according to design standards for imported overseas technology lacked any back-to-basics consideration. A trend emerged and took hold to ensure no such oversight would occur with the high-capacity, high-voltage progress of transformers. This played a major part in later development of new Japanese technology.

In this period, the inner structures of transformers changed dramatically. Problematic non-oil-immersed insulating materials such as paper laminate compounds were superseded by oil-immersed pressboard laminated material or reinforced wood. Insulation materials mainly used in Europe, such as craft board moulded insulation and pressboard insulation cylinders, made their way to Japan. Examination of the insulating properties of winding structures resulted in simple continuous disc winding and minimal shielding between turns at the end of the winding rather than elaborate windings such as the high series capacitance windings previously often used for high voltage. It was possible to apply this to windings of 275kV and over, so it quickly expanded in use. Computers became more widely used at this point, having a significant impact on the increased accuracy of potential vibration analyses.

5.2. The Development of UHV Transformers and UHV Development Technology

(1) Development of UHV Transformers

Around the mid-1970s, domestic 500kV transmission began with Chubu, Chugoku and Kyushu Electric Power Companies, while Tokyo Electric Power Company worked on increasing its bank capacity from 1000MVA to 1500MVA. The production side had been thoroughly immersed in the importance of dust-proofing as a countermeasure against partial discharge. Rigorous control and increased awareness among workers through QC activities has finally led to the standardised production of partial-discharge-free transformers.

Major advances in various electric field analyses and potential vibration analyses using large-scale electronic computers has been characteristic of this period. Collation of the results of these analyses and results of model experiments has increased understanding of oil insulation and made it possible to have more compact insulation.

From the late 1970s to around the mid-1980s, Japan began full-scale development on *UHV*. Research on this was being carried out all around the world at the time as the next stage of voltage and Japan expected to implement it as well.

This required a transformer that could withstand twice the voltage of the 500kV transformer while being subject to the same rail transport size and mass limitations. Initiatives commenced to achieve this objective, using strategic placement of the aforementioned new, compact insulating material. By the end of the 1970s, various companies had reported building prototypes(36)(37)(38).

In 1978, the Special Committee on UHV Transmission was put together from experts in various fields and investigation began on implementing UHV. Besides manufacturing within the rail transport limitations, another technical issue with UHV transformers was ensuring absolute reliability against operating voltage stress during extended operation and all kinds of abnormal voltage stress due to having a greater electric field on the oil channel during operation than existing transformers. To deal with this, various long-term reliability checks were later designed and implemented, with the results reported to the Committee. This is reflected in the later revisions of Japan’s test voltage standards and enabled Japan to have unique, highly reliable insulation standards(39)(40)(41). Photo 5.1 shows a UHV prototype transformer undergoing reliability checks using prolonged voltage impression in a factory field.

Photo 5.1. UHV Prototype Transformer (1979, made by Toshiba)

(2) Adoption of UHV Development Technology

The implementation of UHV was later pushed forward due to the economy transitioning from rapid growth to stable growth in the 1980s. This technology is reflected in transformers of 500kV and lower among various manufacturers, with model changes to downsize and reduce loss. For example, existing core-type 500kV, 1000/3MVA transformers had had two coils in parallel and a single-phase, four-leg core; the adoption of this technology enabled a single coil and a single-phase, three-leg core, which significantly reduced both mass and loss.

This technology was also used to tender for 765kV transformers for overseas; a Japanese alliance (Hitachi, Toshiba, and Mitsubishi) succeeded in getting an order for 765kV transformers for Venezuela. The first shipment of a UHV transformer was sent in 1982 (Photo 5.2). Orders for 765kV transformers were also later successfully received from Brazil and South Africa. The transformers bound for Brazil had a medium voltage of 500kV and a high-voltage impulse test voltage of 1950kV, the same as that expected for UHV in Japan; it was thus later viewed as a prior model (Photo 5.3). The transformers for South Africa had a bank capacity of 2000MVA, the largest ever for a substation (Photo 5.4).

Photo 5.2. The First 765kV Transformer, an 805/3MVA Transformer for Venezuela (1982, made by Mitsubishi)

Photo 5.3. A 765/500kV, 1650/3MVA Transformer for Brazil (1988, made by Toshiba)

Photo 5.4. A 765kV, 2000/3MVA Transformer for South Africa (1985, made by Fuji)

5.3. Popularisation of Underground Substations and Transformer Disaster Prevention Measures[42][43]

(1) Popularisation of Underground Substations

As high-voltage electrical cables began to develop and spread, a movement developed around the end of the 1950s to bring direct high-voltage systems in to urban centres and construct high-voltage networks in cities. The Tokyo Electric Power Company Chiyoda Substation was completed in 1960[44]. This was equipped with a 100MVA, 154kV transformer. Since it was underground, the height of the transformer would affect the construction costs, so this presented strict constraints and various ingenious methods were used, such as onsite assembly. Photo 5.5 shows it in assembled in the factory.

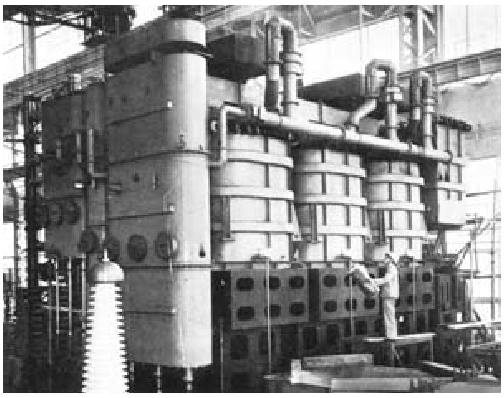


Photo 5.5. The First High-Capacity Underground Substation Transformer

A 154kV, 100MVA Transformer for the Tokyo Electric Power Company Chiyoda Substation (1960, made by Toshiba)

Later, in 1969, shipments were made of 275kV substation transformers. The Shinjuku and Jonan Substations started operating in 1971. Gas insulated switchgears (GIS) began to be used in these 275kV underground substations and later. From the perspective of downsizing the substation, this was extremely effective.

(2) Transformer Disaster Prevention Measures

With Tokyo Electric Power Company's progress on a 275kV network, the short-circuit capacity for the system in the 1980s exceeded the initially-planned 10GVA. When transformers broke down internally, it was a high-energy incident. Accordingly, there was a fear of the worst case scenario, in which the pressure on the transformer tank would exceed its breaking pressure before a circuit breaker could isolate the system, thereby breaking the tank and causing a fire. It was necessary to set some countermeasures in place. A collaborative study between manufacturers and power companies conducted an experiment using gunpowder to simulate increased tank pressure in an internal breakdown and then examined the transformation. This resulted in the proposal of a countermeasure to have tanks separated into single phases joined by an upper duct and sharing a common duct and conservator; larger holes between the tank and the duct relieve pressure increase. This became the standard structure for future underground substations[43].

Regarding explosion-proofing of transformers, the internal tank pressure was obtained and the acceptable accident level determined from the correlation between the amount of gas emitted and the amount of expansion in the tank through collaborative research between power companies and manufacturers in 1975[42]. However, since underground substation transformers had a special three-phase structure, they had a low amount of tank expansion. It was necessary to develop a new structure, as this could not withstand a short-circuit capacity of 15GVA.

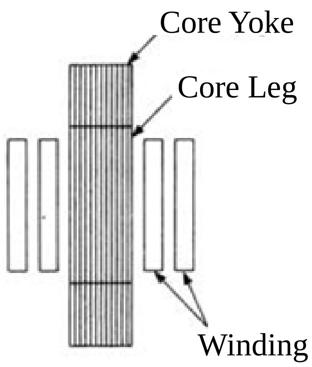
5.4. The Addition of High-Capacity Shunt Reactors

(1) The Necessity for Shunt Reactors

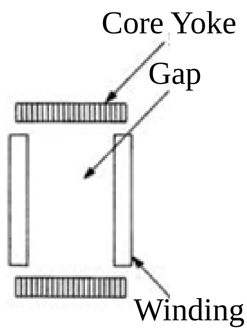
With high-capacity underground substations thus built in urban centres and cable systems connected, at night, when the load was low, a leading load would occur due to cable capacitance. To avoid this, underground substations started being fitted with high-capacity shunt reactors. At first, this was put on the transformer’s tertiary circuit and provided compensation indirectly, but later shunt reactors were directly connected to the 275kV system.

(2) Introduction of Radial Core Shunt Reactors

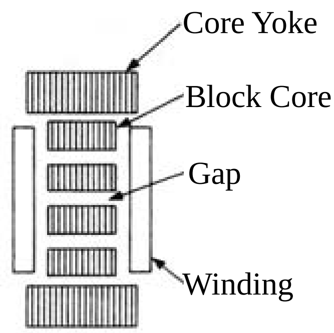
When 275kV was introduced to Japan in 1952, the first 15MVA shunt reactor was introduced to Hirakata Substation for compensation. Later, other relatively low-capacity shunt reactors of 30MVA were introduced from time to time. However, increased cable systems led to the installation of 150MVA reactors at outdoor substations connected to underground substations from 1975 onwards. The main reactors at the time were the air-core type; these had magnetic shieldings around the coil. However, this type had relatively high loss; connecting a shunt reactor would always give a 100% current flow. To reduce loss, due to the strong demand for electricity, a transition began to the *radial core* structure that was standard in Europe at the time and had been in production by Japanese manufacturers from around 1960. This was developed further in the early 1980s. In this case, a spacer made from material with a high Young’s modulus, such as ceramic, was placed between the block core, thereby avoiding variations due to magnetic attraction. Fig. 5.1 shows a schematic diagram of the internal structure of a transformer and shunt reactor. The radial core type shunt reactor later became the standard shunt reactor structure adopted by all companies. In 1994, the first 500kV reactor was set up by the Electric Power Development Company, while the first 250MVA reactor was set up by Chugoku Electric Power Company and Shikoku Electric Power Company. As far as exports go, a record high capacity 765kV, 400/3MVAshunt reactor was dispatched to South Africa in 1985 (Photo 5.7).



(a) Transformer



(b) Air-Core Reactor



(c) Core Reactor

Fig. 5.1. Internal Schematic Diagram of a Transformer/Shunt Reactor

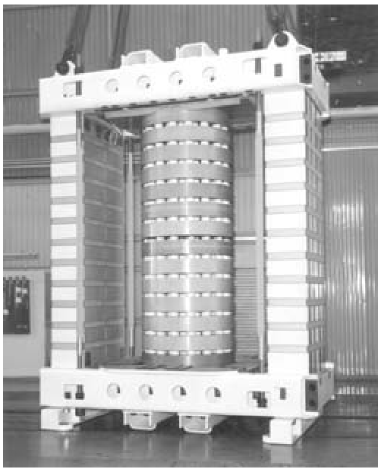


Photo 5.6. Radial Core Assembled

Photo 5.7. A 765kV, 400/3MVA Shunt Reactor for South Africa (1985, made by Toshiba)

5.5. Fire-Proofing Transformers and Development of Gas Insulated Transformers(45)(46)

(1) Fire-Proof Transformers

Before the war, transformers with polychlorinated biphenyl (PCB) insulating oil had been produced from time to time for use indoors at power stations. Since PCB had the same cooling and insulation properties as mineral oil, it was in high demand, particularly in the United States. In Japan, 6-10MVA PCB transformers were produced sporadically from around the mid-1950s for basement substations in urban centres. However, the issue of PCB toxicity meant a strong trend to ban the use of PCB worldwide; in Japan, the use of PCB was declared prohibited in 1974. However, there was not enough demand for PCB transformers to create a demand for a PCB replacement transformer, so everyone soon got by with oil-immersed transformers.

(2) The Appearance and Spread of Gas Insulated Transformers

The first SF_6 gas insulated transformer appeared even before gas insulated switchgears were used. This first transformer was produced by Toshiba based on introduced technology through technical cooperation with American company GE. Rather than using SF_6 as a coolant for direct gas cooling, this transformer had an evaporator built into the tank and ran a heat exchanger using fluorocarbons. This 66kV, 3000kVA transformer was supplied to Daiichi Life in 1967 (Photo 5.8).

Photo 5.8. Japan's First Gas Insulated Transformer (Daiichi Life, 66kV, 3MVA) (1967, made by Toshiba)

At the time, it was quite difficult to design insulation – there was no film insulation technology; like the oil-immersed transformers, paper was used for insulation and it had a low impulse withstand voltage. The film-type gas insulated transformers of today appeared in 1978; these were adopted on the Jōetsu Shinkansen (Photo 5.9).

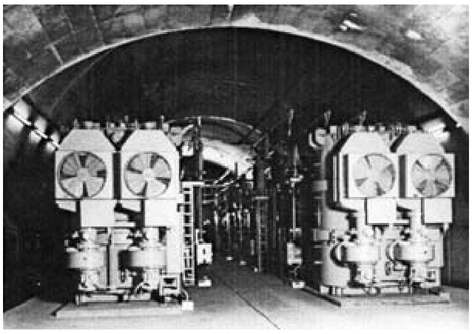


Photo 5.9. A 66kV, 10MVA Gas Insulated Transformer for the Jōetsu Shinkansen (1978, made by Meidensha)

After this, there was a growing demand for transformers for basement substations and subways. In 1982, on-load tap changers were implemented for gas insulated transformers with vacuum valves. The first of these were placed in the Sapporo City Transportation Bureau (Photo 5.10).

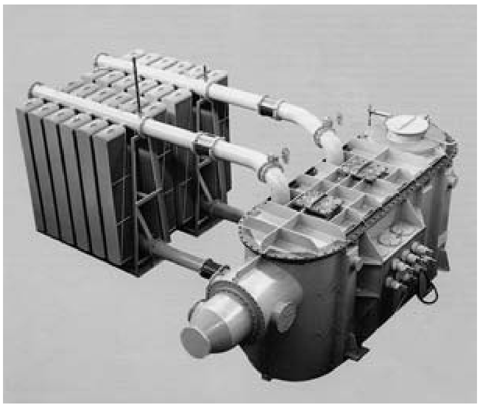


Photo 5.10. A 66kV, 11MVA On-Load Tap Changing Transformer for Sapporo City Transportation Bureau (1982, made by Fuji)

At first, the main film used was E-class heat-resistant polyethylene terephthalate (PET). Later, B-class heat-resistant PET, F-class heat-resistant polyphenylene sulphide (PPS) and H-class aramid paper were also used. While forced-air cooling systems were normal for 10MVA transformers at the time, there was also a strong demand for natural cooling. This was met by improving the winding cooling systems, using highly heat-resistant film and other means and a 20MVA, self-cooled, gas insulated transformer was produced in 1987, followed by a 30MVA version in 1989. The popularity of gas insulated transformers grew as they were widely adopted as replacements after a series of substation fires around the mid-1980s. Fig. 5.2 shows a typical gas insulated transformer structure[46].

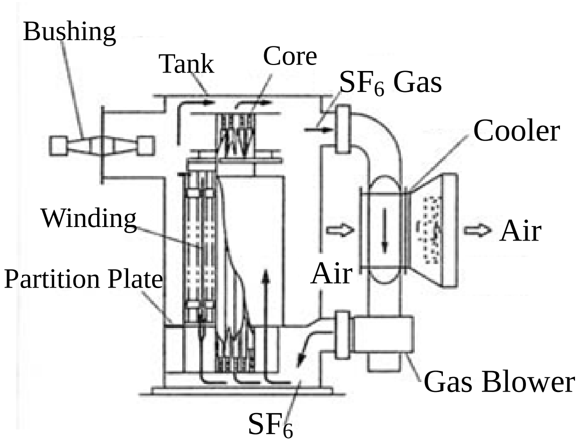


Fig. 5.2. General Structure of a Gas Insulated Transformer

(3) Dry-Type Transformers

While dry-type transformers were used since before the war prior to the popularisation of gas insulated transformers in lower voltage/capacity applications, such as indoor use. In the 1960s, moulded transformers from polyester resin, then epoxy resin, were developed in Europe for these applications as well. Research began in Japan as well from the late 1960s and epoxy resin moulded transformers were introduced in 1974. After that, as capacity steadily increased, the existing dry-type transformers were replaced (Photo 5.11).

Photo 5.11. A 22kV, 13MVA Moulded Transformer for Tokyo City (1994, made by Fuji)

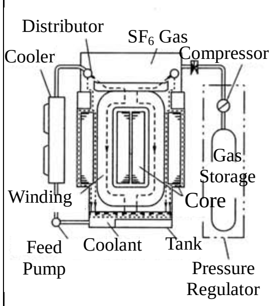
5.6. From Liquid-Cooled, Gas Insulated Transformers to Gas-Cooled, Gas Insulated Transformers

(1) Development of High-Capacity Gas Insulated Transformers

High-capacity gas insulated transformers were first researched in the United States. In the early 1980s, plans were revealed to develop and implement a 300MVA transformer, but these were later suspended due to financial curtailing by the US government. Development in Japan commenced by Kansai Electric Power Company and Mitsubishi Electric, inspired by the American plans. At first, SF_6 gas alone was thought to be inadequate for cooling high capacity transformers and consideration was given to other liquids for cooling. Mitsubishi came up with an evaporative cooling system developed by American company WH, whereby perfluorocarbons were dropped down from above the winding, cooling them by heat absorption as they evaporated. In 1980, a 77kV, 40MVA transformer was delivered to Hokusetsu Substation. Later, work began on changing to liquid flow-down for high-capacity transformers. Meanwhile, from 1983 onwards, Toshiba began work on development, together with Tokyo Electric Power Company. This involved the adoption of a separate cooling system for directly cooling the winding, using aluminium sheets developed by American company GE for the windings, PET film for the insulation, rolling up metal cooling plates inside the winding and passing perfluorocarbon liquid through it. Hitachi also started working on perfluorocarbon transformers together with Chubu Electric Power Company. They came up with an immersion cooling system, whereby a tub made from FRP cylinder around the interior in the tank was filled with perfluorocarbon liquid to directly cool the interior. The general structures and features devised by each company are given in Table 5.1[46]. All the companies' methods had to solve a number of points, which took time to develop and implement. In 1989, Toshiba succeeded in developing the world's first 154kV, 200MVA, high-capacity, gas insulated transformer for the Tokyo Electric Power Company Asahi Substation (Photo 5.12). This was followed by the development of 275kV, 300MVA and 250MVA transformers in 1990 by Tokyo Electric Power Company, Kansai Electric Power Company and Chubu Electric Power Company[47][48][49].

Photo 5.12. The World's First High-Capacity Gas Insulated Transformer
A 154kV, 200MVA Transformer for the Tokyo Electric Power Company Asahi Substation (1989, made by Toshiba)

Table 5.1. Overview of Liquid-Cooled, Gas Insulated Transformer Structures

<table>
<tr><td colspan="2" rowspan="2">Cooling System</td><td colspan="3">Liquid-Cooled</td></tr>
<tr><td>Flow-Down</td><td>Immersion</td><td>Separate</td></tr>
<tr><td colspan="2">Configuration Example</td>
<td>
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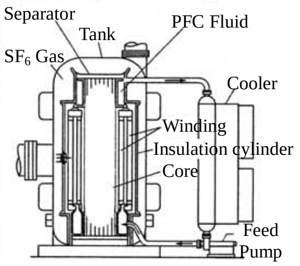
<td>
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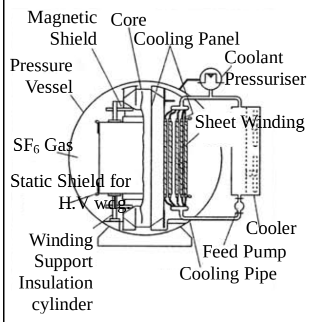
<td>
</td></tr>
<tr><td colspan="2">Winding Structure</td><td>Rectangular Plate Winding</td><td>Disc Winding</td><td>Sheet Winding</td></tr>
<tr><td colspan="2">Core Structure</td><td>Shell Type</td><td>Core Type</td><td>Core Type</td></tr>
<tr><td colspan="2">Voltage (kV)</td><td>275</td><td>275</td><td>154, 275</td></tr>
<tr><td colspan="2">Capacity (MVA)</td><td>300</td><td>150, 250</td><td>200, 300</td></tr>
<tr><td colspan="2">Nominal Pressure (MPa)</td><td>0.1-0.2</td><td>0.35</td><td>0.4</td></tr>
<tr><td colspan="2">Main Body Gas Capacity (m^3)</td><td>80-100</td><td>23.4, 24.4</td><td>130, 135</td></tr>
<tr><td colspan="2">Cooling Medium</td><td>PFC Fluid</td><td>PFC Fluid</td><td>PFC Fluid</td></tr>
<tr><td colspan="2">Winding Insulation Coating</td><td>PPS Film</td><td>Aramid Paper</td><td>PET Film</td></tr>
<tr><td rowspan="2">Insulating Medium</td><td>Winding Interior</td><td>SF_6 Gas</td><td>PFC Fluid</td><td>PET Film</td></tr>
<tr><td>Ground</td><td>SF_6 Gas</td><td>SF_6 Gas</td><td>SF_6 Gas</td></tr>
<tr><td colspan="2">Coolant Circulation System</td><td>Forced Circulation</td><td>Forced Circulation</td><td>Forced Circulation</td></tr>
<tr><td colspan="2">Characteristics</td><td>Mix of SF_6 Gas and Coolant
Low operating pressure by means of pressure regulator</td><td>SF_6 Gas and Coolant Separate
Core and winding immersed in coolant inside insulation tub</td><td>SF_6 Gas and Coolant Separate
Core and winding cooled by cooling panel</td></tr>
</table>

Survey Reports on the Systemization of Technologies; No. 4, March 2004
National Museum of Nature and Science, Japan

(2) The Challenges of Liquid-Cooled, Gas Insulated Transformers

These were completely different in structure from the existing oil-immersed transformers. While each had numerous issues to be solved in various ways, these hurdles were systematically cleared. The flow electrification incidents had left Japanese researchers and developers with well-grounded technology development capabilities, which saw them through all the reliability testing right to the implementation stage.

However, in contrast to the simple structure of the existing oil-immersed transformers, which the same oil for both insulation and cooling, these transformers required a special structure for cooling the winding, which was costly, and also used very expensive perfluorocarbon fluid for cooling. These transformers cost two to three times more than the existing oil-immersed transformers, which made it difficult for them to be widely adopted.

(3) Achievement of High-Capacity, Gas-Cooled Transformers

Underground substations required shunt reactors as well as transformers. Toshiba started researching direct gas cooling, as it was having difficulty using a separate cooling system incorporating a blocked core cooling panel for gas insulation of these reactors. The success of this gave hope to the idea of 300MVA gas-cooled transformers, and development changed direction. In 1994, a 275kV, 300MVA transformer for the Tokyo Electric Power Company Higashi-Shinjuku Substation was successfully produced with a gas cooling system. Photo 5.13 shows the exterior of this transformer, while Photo 5.14 shows the interior, which looks no different to an oil-immersed transformer(50). Previously thought impossible, gas cooling was achieved by increasing the gas pressure, increasing the heat resistance of the insulation, developing a high-capacity, high-pressure gas blower, keeping an even winding temperature by controlling the gas flow inside the winding, and various other technology. Japan's capabilities in developing new technology contributed greatly to this achievement. Currently, Tokyo Electric Power Company is using these gas insulated transformers instead of oil-immersed transformers in its underground substations. This system was also adopted in a 220kV, 300MVA transformer for Chugoku Electric Power Company as well as the first 345kV, 400MVA transformer for export to Australia. The latest liquid-cooled, gas insulated transformer was a 275kV, 450MVA transformer – the highest capacity gas insulated transformer for an underground substation – completed by Hitachi in 1998 with an immersion system and supplied to Chubu Electric Power Company (Photo 5.15).

Photo 5.13. A Gas-Cooled, 275kV, 300MVA Transformer for the Tokyo Electric Power Company Higashi-Shinjuku Substation (1994, made by Toshiba)

Photo 5.14. Interior of the Higashi-Shinjuku Substation Transformer

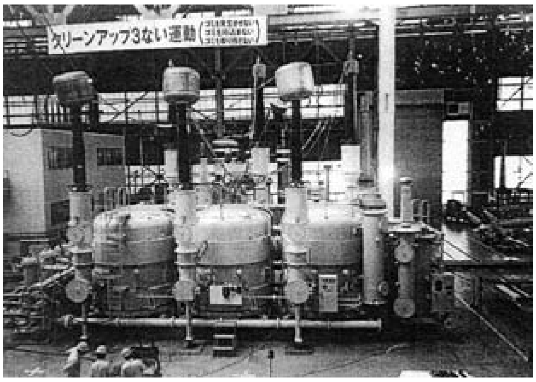


Photo 5.15. The Highest-Capacity Gas Insulated Transformer, a 275kV, 450MVA Transformer for the Chubu Electric Power Company Meijo Substation (1998, made by Hitachi)

5.7. UHV Demonstration Testing Equipment

(1) Resumption of UHV Transmission Plans

Steps had been taken towards technology development for UHV transmission, including the establishment of the Special Committee for UHV Transmission in 1978, basic studies, developmental research and demonstration testing. This also included the selection of 1000kV as the nominal voltage and 1100kV as the maximum voltage. Detailed conceptual designs and studies on basic specifications for UHV as well as manufacturers' studies on component models and prototype transformers made it clear that it was possible to achieve sufficiently reliable equipment. The development of high performance zinc oxide arresters also meant that the test voltage could be reduced and rationalised by 70%[39]. Although a conclusion was reached on UHV transmission in 1982, the economy transitioned from high growth to stable in the 1980s, which meant a major delay in the implementation of it and a suspension of studies on UHV.

However, the postponed UHV plan began to be implemented by Tokyo Electric Power Company in the 1990s and the early 2000s. In 1995, a proposal suddenly emerged for two years of demonstration testing. Testing began on full-scale models based on the production models that had been abandoned in the 1980s to eliminate technical issues and determine specifications.

(2) UHV Demonstration Testing Transformers

The rated values for demonstration testing transformers were set at voltages of 1050/525/147kV, bank capacity of 3000MVA, and tap range of 7%. Hitachi, Toshiba and Mitsubishi worked on one phase each. The designs emulated the already-developed insulation technology, with single-phase 1000MVA on a two-tank structure with bushing out between the two tanks. Prior to the demonstration testing models, a single tank test piece was produced, with the actual model being produced following limit tests. The demonstration testing model was completed in 1993 and it was tested for two years at the Shin-Haruna Substation[51]. Photo 5.16 shows the UHV demonstration testing model in site. During testing, issues emerged with the field test circuit and with flow electrification of a different type than that experienced with the 500kV transformer. The new issues discovered with UHV implementation demonstrated the significance of carrying out demonstration testing. While current UHV lines are operated at 500kV, there are new issues emerging that did not occur previously, such as connected 500kV transformers experiencing insulation failure due to lightning surges – investigation into the cause of which showed that voltage on UHV lines enters transformers with a longer wavetail than a normal waveform, causing greater stress within the transformer.

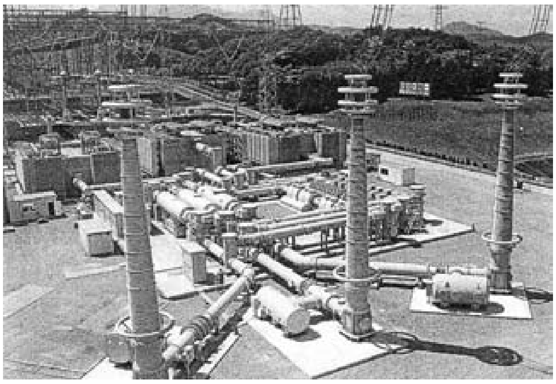


Photo 5.16. UHV Demonstration Testing Transformer at the Tokyo Electric Power Company Shin-Haruna Substation (1993, from left made by Toshiba, Mitsubishi and Hitachi)

Initially, the plan was to begin operation at the start of the 21st century, but that plan is now on hold and it is unclear when UHV will be implemented, due to the plateauing demand for electricity following the bursting of the bubble economy.

5.8. DC Conversion Transformers and DC Transmission

(1) The Emergence of DC Conversion Transformers

The first DC conversion transformers in Japan were 275kV, 368MVA and 353MVA transformers made by Mitsubishi Electric in 1964 for the Electric Power Development Company Sakuma Frequency Converter Station (Photo 5.17)(52). These used mercury arc valves made in Sweden. In 1970, Electric Power Development Company continued prolonged demonstration testing using Japanese-made thyristor valves in place of mercury arc valves. Hitachi and Toshiba also took part in manufacturing conversion transformers. Technical issues with conversion transformers at the time included *DC bias magnetism* in the core due to the excitation current being ridden by the DC component caused by differences in valve control angle between each phase, increased noise due to this, problems insulating the DC voltage, and further loss and temperature increase on harmonic currents. The first thyristor valves in operation were in-tank, oil-immersed thyristor valves at the Tokyo Electric Power Company Shin-Shinano Frequency Converter Station. To allow compatibility between Tokyo Electric Power Company and Chubu Electric Power Company, DC conversion was used between the 50Hz and 60Hz converter stations. The transformers had a rated value of 187MVA, 275kV/110kV.

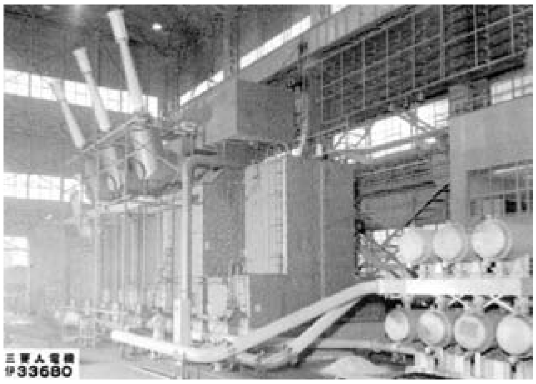


Photo 5.17. The First Frequency Converter Transformer at the Electric Power Development Company Sakuma Frequency Converter Station (1964, made by Mitsubishi)

(2) The Start of DC Transmission

DC transmission started in Japan in 1979 on the Electric Power Development Company

Hokkaido-Honshu connection. In 1978, Hitachi supplied the Hokkaido transformer, while Toshiba supplied the Honshu transformer. These had rated values of 187MVA, 275/125kV, about the same as the Shin-Shinano transformer. At the second phase, the DC voltage was raised ±250kV, while the DC withstand voltage was doubled to ±450kV. Since DC insulation had different voltage distribution ratios from AC insulation for the insulating material and the oil duct, the insulation structure had to be different from the existing AC insulation. Model testing was carried out on insulation structures with double the DC withstand voltage, followed by actual production units. The second phase was shipped out in 1979. Photo 5.18 shows the exterior of a 250kV DC transmission transformer.

Photo 5.18. A 250kV DC Transmission Transformer at the Electric Power Development Company Hakodate Converter Station (1979, made by Hitachi)

(3) Power Compatibility and 500kV DC Transmission

Further expansions were made to enhance compatibility between power companies. Fig. 5.3[53] shows a distribution map of converter stations accompanying DC conversion in Japan. There are two DC transmitters, three frequency converter stations (including one that had not yet started operating) and one back to back converter substation for stabilising the network between Chubu Electric Power Company and Hokuriku Electric Power Company, interconnected on the same frequency. Most noteworthy here is the DC link between Shikoku and the Kii Peninsula and DC transmission aimed at providing Kansai Electric Power Company with power generated by Shikoku Electric Power Company and Electric Power Development Company. While the plan was to initially operate at ±250kV, it was already equipped for future ±500kV operation, with DC reactors, etc. In preparation for this, development began on 500kV equipment, with manufacturers carrying out model testing on DC insulation and reliability checks carried out through long term experimenting at the Kansai Electric Power Company Yamazaki Laboratory. Hitachi, Toshiba and Mitsubishi produced these transformers and reactors, supplying them in 1997-1998 (Photo 5.19). The DC transmission transformers have rated values of 872MVA, 500kV – the highest ever capacity for conversion transformers.

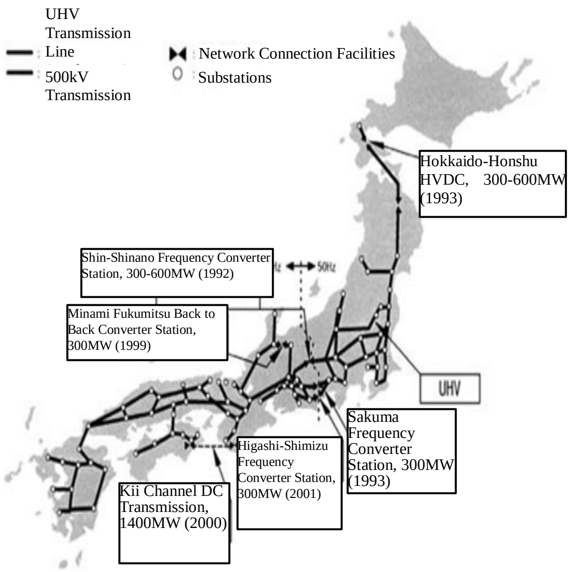


Fig. 5.3. The Electrical System Structure in Japan

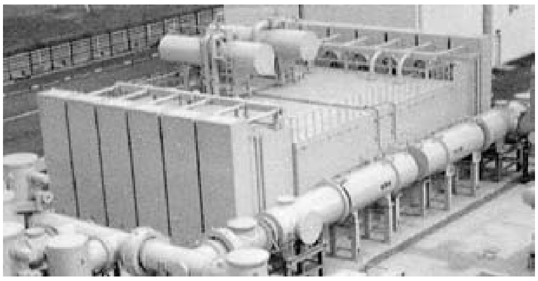


Photo 5.19. A 500kV DC Reactor at the Shikoku Electric Power Company Anan Frequency Converter Station (1997, made by Mitsubishi)

5.9. Reducing Loss

(1) Transformer Loss Evaluation

For quite some time it has been normal overseas when operating a transformer in a network to calculate the price of loss produced by that transformer as an associated cost and add it to the purchase price of the transformer when estimating its value. While there are differences between load loss and no-load loss in this estimate, the estimates increased after the 1973 oil crisis. For some countries, particularly those that depended on energy from other countries, the price quadrupled to \$7000/kW no-load loss, \$3000/kW load loss. This meant the loss estimate had a greater weighting than the price of the unit, resulting in a situation in which the main competitive advantage went to how much the loss could be reduced by.

(2) Reducing Loss

In the 1980s, the domestic market entered a time of long-term low growth due to changes in demand structure. Competition between manufacturers intensified over the smallest of matters. Japan had not familiarised itself with loss price evaluation like overseas and price was evaluated in terms of cost only. However, given this situation, companies soon learned that the amount of loss as well as cost was a key factor in gaining orders; the various companies competed to reduce loss. Applying technology developed for UHV to machinery built for 500kV and under made it possible to reduce the mass and simplify the structure of those machines; accordingly, various companies competed to apply this technology to reduce the mass and simplify the structure of their products.

(3) Measures to Reduce Core Loss

Measures to reduce core loss started with the use of higher quality materials for the core, followed by the use of *magnetic-domain-refined silicon steel sheets* with magnetic domains marked out mechanically by lasers, and the use of thinner silicon steel sheets than the standard 0.35mm with thicknesses of 0.3mm, 0.27mm or 0.23mm. Structural changes included the use of *step-lap joint cores*, in which the core junction takes a staircase pattern. Another effective method to reduce core loss is to reduce the transformer mass by reducing the dimensions of the insulation. The most effective way to reduce core loss is to reduce mass of core material. However, reducing the loss in the copper wire is not very effective. Reducing core loss by improving core materials has mainly been done in Japan since the introduction of grain-oriented silicon steel sheets. The technological strength of Japanese steel manufacturers has led the world with the development of *high grain-oriented silicon steel sheets* in 1968, the introduction of 0.23mm sheets and the development of magnetic-domain-refined silicon steel sheets. Currently, Japanese manufacturers virtually have the monopoly on high-quality materials. Transformer manufacturers were quick to adopt these materials, giving them an advantage against overseas competition. The materials used today have around two-thirds the loss than in the 1960s, when grain-oriented silicon steel sheets were first used. Taking into account the reduced loss from improvements in insulation technology and other factors in the materials used, it is around 50% better.

(4) Measures to Reduce Load Loss

In contrast to core loss, improving materials has little effect in reducing load loss. Reduction in load loss is mainly achieved by reducing eddy current loss in the windings through the use of multiconductor cables, containing several thin conducting wires all insulated together, or *transposed cables*, with an odd number of conducting wires positioned in two rows and joined mechanically at a fine pitch. Other methods include mounting a magnetic shielding for stray load loss occurring in the tank or inner structural materials, narrowing the width of the iron materials, or creating a slit. Where transformers for export were expected to have very high loss evaluation, a method was adopted of decreasing the current density and thereby reducing the resistance loss, even though the price of the transformer increased as the mass increased.

It was possible to reduce load loss in machines such as 500kV substation transformers, which had a single-phase structure and could alter the number of windings in parallel, by applying technology developed for UHV. The amount of copper wire used in the 1000/3MVA transformers could be greatly reduced by changing them from a two-main leg structure into a one- main leg structure, but this was less effective in other transformers. Existing insulation designs had concentrated on minimising potential vibration. High series capacitance windings did not have a very workable structure; results from investigating potential vibration and failure mechanisms in windings made it possible to use ordinary continuous disc windings at 275kV and higher, which was previously thought difficult to implement. The use of transposed cables with thin conducting wires made it possible to reduce eddy current loss, which accounted for as much as 30% of resistance loss, by more than half at high capacity. Such improvements to insulation greatly contributed to workability and loss reduction.

5.10. Popularisation of Low-Noise Transformers and Simplification of Soundproofing Measures[54]

(1) Necessity of Low-Noise Transformers

The demand for low-noise transformers emerged sporadically in the 1950s, but in very limited circumstances. However, as society later became more affluent, there were more sensitive reactions to industrial pollution issues, including noise. Noise reduction was first carried out on transformers at secondary substations located near residential areas. In the 1970s, urban noise control regulations were made stricter and even high-capacity transformers at primary substations in the outskirts of urban areas had to reduce their noise omissions at night to 45dB at the substation boundary line. Air-insulated machines were superseded by gas-insulated switchgear (GIS) in the 1970s, drastically reducing the land area occupied by substations. Since the noise specifications imposed on transformers were obtained by calculating backwards from the level at the boundary, this meant even lower values than before, e.g. 60dB.

(2) Low-Noise Measures and their Changes

Measures taken on transformers to meet these specifications include surrounding the tank area with sound barriers such as *steel sheets*, concrete or *concrete panels*, or reducing the amount of noise generated through magnetic distotion of the core. Other methods included reducing fan rotations to reduce the noise produced by the cooling system, or fitting the cooler with a soundproofing wind tunnel lined with sound absorbing material.

While many ingenious methods were used to make it easier to assemble transformer sound barriers around transformers on site, foundation work and assembly required a lot of time and effort, which did not match the course of action prescribed by power companies at the time of keeping onsite work as simple as possible.

During this time, work began on improving the core material, which was a source of noise. High grain-oriented silicon steel sheets had better crystal orientation as well as better magnetic and magnetostrictive properties and better tensile strength from the insulating film. Accordingly, it could reduce the noise generated by the existing grain-oriented silicon steel plates by 2-4dB. This has been adopted as the norm since the late 1970s to the present day. While step-lap joint cores were initially used as a means of reducing no-load loss, these also reduce the disturbance to the magnetic flux flow at the joint and consequently reduce the magnetic and electromagnetic vibration, which was found to reduce the amount of noise by up to 15dB, depending on the circumstances. These were first used in secondary substation transformers and then became the norm for 30MVA transformers with no sound barriers. These were also used for high capacity and gradually increased in use, although this meant poor core stacking workability. By using this in conjunction with a direct-mounted soundproofing plate attached to the tank beam, or combining it with a reduced magnetic flux density, it was possible for even 300MVA transformers to operate at low noise levels of 60dB without sound barriers, thereby drastically reducing the amount of onsite work. Figs. 5.4 and 5.5 show the structure of a direct-mounted soundproofing plate[54]. Photo 5.20 shows the exterior of a 300MVA transformer operating at 60dB without a sound barrier.

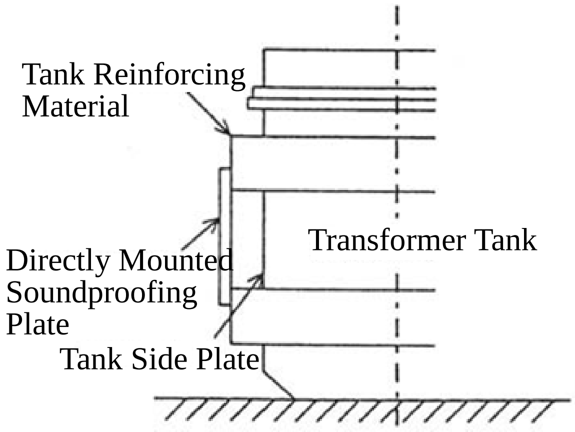


Fig. 5.4. Structural Diagram of a Direct-Mounted Soundproofing Plate

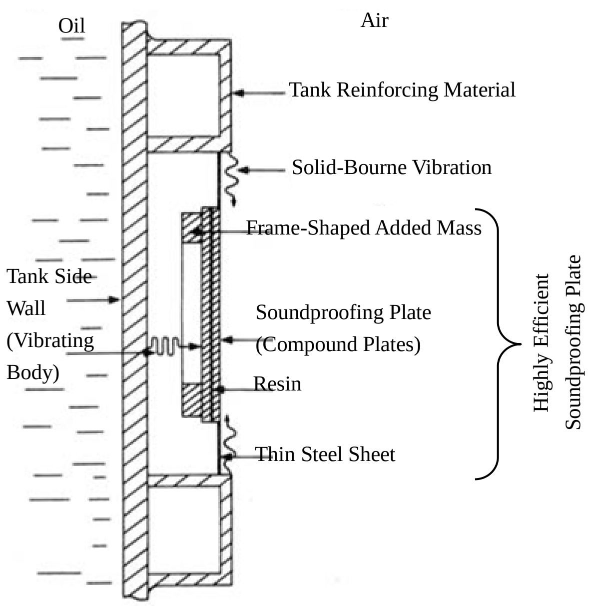


Fig. 5.5. Detail of an Example Installation of a Direct-Mounted Soundproofing Plate

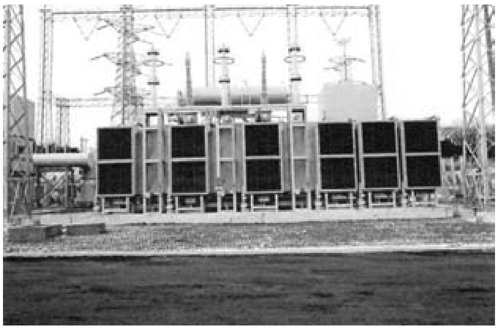


Photo 5.20. A 300MVA Transformer Operating at 60dB without a Sound Barrier (Tohoku Electric Power Company Ishinomaki Substation) (1992, made by Hitachi)

Thus, in recent times, large-scale sound barriers requiring a lot of work on site are only used in specifically-designated low-noise circumstances. Generally, onsite work has been simplified through the use of direct-mounted soundproofing plates and core structures or through magnetic flux density.

5.11. Changes in Transportation Conditions and the New Disassembled-for-Transport Transformers

(1) Changes in Transformer Transportation Conditions

There is a major difference between electricity use during the day and during the night. An increasing proportion of electricity is generated through pumped storage to combat peak loads. High-capacity pumped storage power stations have been being built since the 1970s, while the greatest issue has been the transportation of high-capacity equipment due to the limitations imposed by the location of these power stations. At a time when equipment reliability was a top priority for transformers, it was unthinkable to adopt the old disassembled-for-transport system; transformers had to be transported in their factory-tested condition, with the onsite product an exact reproduction of the factory product. In some cases, the transformer capacity was equal to two or three generators combined. Accordingly, designing and manufacturing a product that would fit within the size and mass constraints for transportation could only be done by increasing the number of partitions; sometimes a single-phase unit would be split into two or three partitions. A 500kV, 680MVA transformer manufactured in 1977 for the Kansai Electric Power Company Oku-Yoshino Pumped Storage Power Station had a nine-part structure, with a single phase split into three partitions. Including the on-load voltage regulator, it comprised 12 partitions (Photo 5.21). By the 1980s, both pumped storage power stations and substations faced stricter limitations on transport routes due to the rationalisation of freight transport, as well as stricter size and mass restrictions for transportation. With an increasing number of substations being located in remote rural areas far from urban centres as well as growing difficulties with road transport, transportation costs rose significantly. In the event of a fault with an existing transformer that meant it had to be returned to the factory for repairs, there were fewer and fewer means of transporting it. Something had to be done to resolve this.

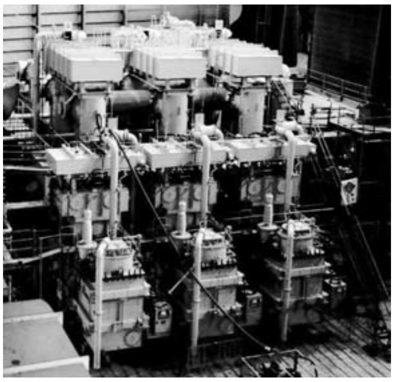


Photo 5.21. A Transformer Transported in Nine Partitions, a 680MVA Transformer for the Kansai Electric Power Company Oku-Yoshino Power Station (1977, made by Toshiba)

(2) The New Disassembled-for-Transport Transformers

The first endeavour to solve this issue was undertaken by Kansai Electric Power Company and Mitsubishi Electric. In contrast the previous disassembled-for-transport system, they packed the coils together in film using a structure that prevented moisture absorption during disassembly and onsite reassembly, thereby omitting any onsite drying. Further ingenuity with the core provided a structure that was easier to dismantle and reassemble, while the use of a dustproof working chamber meant that onsite assembly conditions could match those at the factory. This provided a structure and working system that showed concern for power companies' emphasis on reliability. In 1984, a 275kV, 300MVA transformer was supplied to the Kobe Substation as a model case[55]. This move was later taken up by other power companies and manufacturers, who worked on new core structures, made improvements to dustproof working chambers, investigated the necessity of onsite field testing as well as what should be tested, and also brought out testing equipment. In 1994, the existing 500kV, 1000MVA transformer, which had comprised three single-phase structures, was configured into a three-phase structure. As well as dramatically reducing transport costs, this also reduced installation space and loss, meaning it could benefit power companies. From then on, more and more power companies adopted this system and it became the norm. Photo 5.22 shows an integrated three-phase, 1000MVA, 500kV transformer. The adoption of this system meant no more specialised railcars. It could be transported on an ordinary truck trailer and could be transported from the factory or nearest port, meaning that the time and labour required to operate special railcars was also no longer required. As well as eliminating transportation limitations, it also reduced the time required for onsite assembly, as well as other benefits. This system is likely to increase in use regardless of any future transportation difficulties.

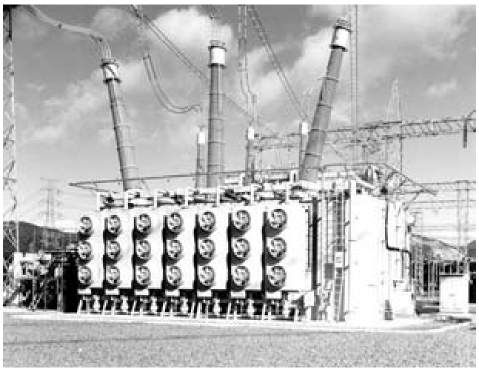


Photo 5.22. A New, Integrated Three-Phase, Disassembled-for-Transport, 500kV Transformer at the Chubu Electric Power Company Seibu Substation (1996, made by Toshiba)

5.12. Diagnosing Deterioration and Prolonging Lifespan[56]

In the 1990s, amidst the slumped demand for electricity and the liberalisation of the electricity market in the wake of the burst of the bubble economy, power companies starting trying to get more from their investments in power distribution facilities. One of the measures taken was to reduce expenditure by prolonging the lifespan of their transformers, many of which were set up during the booming post-war demand for electricity and were now reaching the end of their 30-year lifespan. Specifically, they would calculate the remaining lifespan of the transformer and use it to the very end. Despite a higher likelihood of damage to the transformer, they would keep using it until the damage actually did occur. This was a dramatic change of direction from the previous approach of emphasising reliability. It became common to collect insulating material from ageing transformers, specifically, the insulation from the winding thought to be the most degraded, determine the degree of degradation by the *degree of polymerisation* and the tensile strength of the paper, note down the data and compare it to data from samples of insulation from easily accessed components inside the transformer, such as leads, and use the correlation between the two to simply determine the lifespan of the transformer and calculate the remaining lifespan. Power companies and manufacturers collaborated to standardise the evaluation criteria for determining the lifespan of transformers; these were published in 1999(56). Currently, nuclear energy transformers are beginning to be updated with the view that they would need to be updated anyway due to the high usage load factor on them since the 1970s and also in light of the fact that they can then be expected to operate for another 30 years. However, fossil fuel power transformers are not being updated, due to a low average load factor resulting from their use as peak load generators rather than base load generators. Further, transformers that were manufactured earlier on operate less efficiently and are uneconomical; these are steadily being scrapped, with an increasing number of facilities being shut down.

Meanwhile, with the previous emphasis on reliability, there is an excessive number of substation transformers compared with those found overseas. These are operated in such a way as to avoid an overload even in the event of a breakdown, so the average load factor is lower than for power stations. Even transformers that have reached their lifespan of 30 years have little degradation, so provided there is no major change in electricity demand, these are expected to continue being used for a long time, while being checked for degradation.

6.1. Pre-War Transformers

(1) Transformers in the Early Developmental Period

To this point, we have examined the course of technological progress on transformers stage by stage. Let us now systematically examine the technology in each period.

The early developmental period began by copying technology from overseas. Development on transformers began about 10 years after this copying started. Initially, electricity distribution started out at low voltages of around 1000V and was used for lighting. As other uses for electricity began to develop, transformers began to be adapted for higher voltage and higher capacity. While they were air-cooled and air-insulated to begin with, oil was soon proposed as a medium for insulation and cooling and mineral oil was put to use. However, core materials at the time consisted of laminated mild steel sheets, which carried the problem of significant loss, as well as properties that change over time to add to the loss. This problem was significantly improved with the invention of silicon steel sheets in 1900 by Robert Hadfield of the United Kingdom; these were industrialised and used in transformers in 1903. High capacity transformers made rapid progress in Japan with the import and application of silicon steel sheets in 1910. Technical cooperation with overseas manufacturers began around this time and technology developed overseas began to be introduced to Japan, accelerating the progress of development of transformer technology in Japan. Another issue with high capacity was cooling. While at first, transformers generated little heat and natural cooling was sufficient, high voltage and high capacity required two stages of cooling: cooling the interior and overall cooling of the entire transformer. The natural convection of the oil was used to cool the interior, but heat radiation from the tank alone was not sufficient for overall cooling. Since radiators had not yet been developed, a water-cooling method was introduced, with water pipes built into the tank. Radiator cooling started with the development of the radiator in 1916, but since the welding of the laminate was by no means perfect, there were often oil leaks, meaning this method was not yet widely adopted. In the 1920s, improvements in cooling designs and radiator production technology saw an increase in use of self-cooled transformers; by the late 1920s, Japan had made a transformer with world-record-breaking capacity. After that, as further progress was made on capacity, forced-oil systems became more commonly used to cool the interior, forcibly circulating oil with a pump. While Germany and other countries had long used forced-oil, forced-air cooling systems, Japan did so much later in 1926. The cooling unit system commonly used today was adopted in the 1940s.

(2) Post-War Success of the Transformer

The Showa Period saw in the age of transformer development. This was triggered by Japan’s first domestically-produced 154kV transformer, brought out in 1926, three years after the first imported ones. Following the continued successful operation of this transformer, overseas imports dropped off as domestic products gained almost exclusive predominance. Further development of electricity on the Korean Peninsula played a major role in the spread of transformers. Given the success of the first large-scale power generation projects, other power generation projects steadily got under way, with some record-breaking products manufactured. One of these was the implementation of the first extremely-high-voltage 220kV transformer in the East, a 220kV, 80MVA transformer completed in 1939. Later, a 100MVA transformer was produced – equal to the highest capacity transformer in the world at the time. In some respects, Japanese transformer production technology had reached world-class level. However, although the level of technology at the time might not have been a far cry from world-class, given the incidents of melted cores, inadequacies in production technology and quality control, the strain of pushing to the limit and producing a record product started to show.

The first high-capacity transformers of 10MVA and over were disassembled for transport, having no other means of transportation. They were then reassembled and re-dried onsite. This meant assembly took several days. All of the high-capacity transformers on the Korean Peninsula were disassembled for transport, and the lack of sufficient work management and drying during onsite assembly was thought to be one cause of the melting cores. While assembled transportation got off to a slow start due to more limited rail transport constraints than in the West, in the late 1920s, assembled transportation began to be the trend, with special railcars that made effective use of the transportation limitations as well as methods to reduce the mass of the load transported by substituting oil with nitrogen. In this way, transformers up to 39MVA had been transported by rail before the war.

(3) Lightning-Protected Design and Impulse Testing

A major technical consideration in the pre-war era was how to protect transformers against accidents from lightning surges. Following a publication in 1915 by German engineer Karl Wagner stating that the behaviour within a transformer in response to a surge can be interpreted through travelling wave theory in the same way as power lines, studies were carried out in many countries on lightning surges and windings. These studies were carried out in Japan as well, mainly at universities. Since the areas near the ends of the transformer windings were often the parts that were damaged, a method was adopted in Japan around 1920 of reinforcing the insulation around those areas, while other countries developed their own particular windings to withstand surges. However, unlike the West, which had a directly-grounded neutral point, Japan used high resistance grounding; accordingly, the voltage distribution from lightning surges would be different. These windings were not adopted as it was thought that they could not be. However, manufacturers later took potential distribution measurements and confirmed that <u>*surge-proof windings*</u> and <u>*partially shielded windings*</u> did actually improve potential distribution; these windings were gradually introduced in the 1930s. However, the transformers at the time using this design were not actually proven to have any special lightning resistant properties. In the 1920s, debate began in the United States on the issue of insulation coordination between power lines and transformers, etc. In the 1930s, GE started carrying out the first impulse tests with the aim of finding proof on this issue. Impulse testing later became standardised in the United States; inspired by this, Japan also formed a standardisation committee and published its own standards, following much discussion, in

1945, just before the war ended. Impulse testing was first carried out in Japan in 1937 on a 154kV transformer for what was then Japanese Government Railways. This had a winding structure with reinforced insulated ends and demonstrated the validity of the insulating structures of the time.

(4) On-Load Tap Changers

Another technical topic of this period was the development of on-load tap changers. On-load tap changers, which changed taps during operation to maintain a fixed voltage to balance the changes in the load, were developed around the mid-1920s to temporarily bridge a different tap position while the tap is changing. A system of using a current limiting reactor to suppress cyclic current during this process was first developed in the United States, followed by a method developed in Germany using resistance. The American current limiting reactor system was first adopted in Japan, with the first product built in 1930. The next few years after that saw rapid development and the implementation of high capacity, with voltage regulators introduced in 1933 to control the flow of electricity. The German-style resistance tap changers were implemented in Japan in 1935.

(5) Non-flammable Transformers

Polychlorinated biphenyl (PCB) was developed in the United States in the 1920s as a non-flammable insulating oil. This was later produced in Japan and first used in a transformer in 1940. However, the war ended without it coming into widespread use due to the issue of cost. While dry-type transformers had also long been used as non-flammable transformers, they were also not widely adopted due to cooling and voltage limitations.

(6) Setting Standards

Reliability-based standards began in 1922 with the setting of Standard JEC-9 for electrical equipment including rotating machines. Standard JEC-36 for transformers was established in 1934, thereby ensuring uniform quality for transformers as a indent product. Japan Standard JES31 was established in 1926 for pole-mount transformers, standardising their characteristics, structure, etc. JEC-36Z was issued as a wartime standard to ease up the temperature restrictions of JEC-36 during the war. JEC-110 on impulse testing was issued just before the end of the war, as mentioned previously, laying the framework for the post-war commencement of extremely- high-voltage power transmission.

(7) Systematisation of Pre-War Transformer Technology

The above outline of pre-war transformer technology is shown in Fig. 6.1. Figs. 6.2 and 6.3 show the timewise trends in technology and production in terms of the major transformer issues of reliability, high capacity, high voltage, environment and accessories. Fig. 6.2 shows the main technology developments for each of these issues and also notes the technological progress of the period. The numbers to the top right corner of the balloon boxes correspond to the numbers on the photographs in the main text. Fig. 6.3 shows the timewise trends in major technologies. The shaded areas represent technologies that were used concurrently with other technologies but mainly used in high-capacity transformers. Areas marked with diagonal borders indicate that it took some time to switch to these technologies. Table 6.1 shows the development period for the main technologies and products.

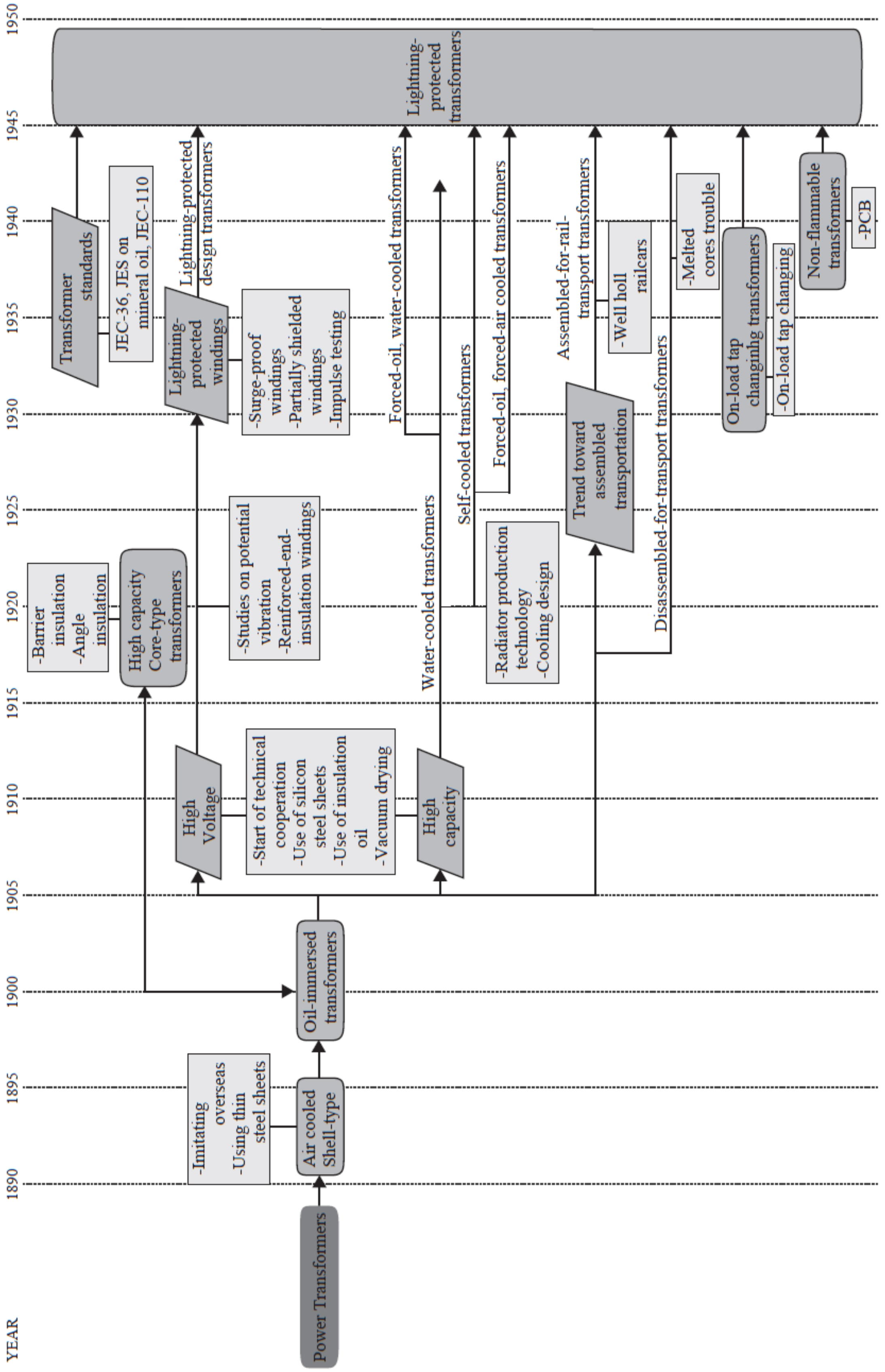
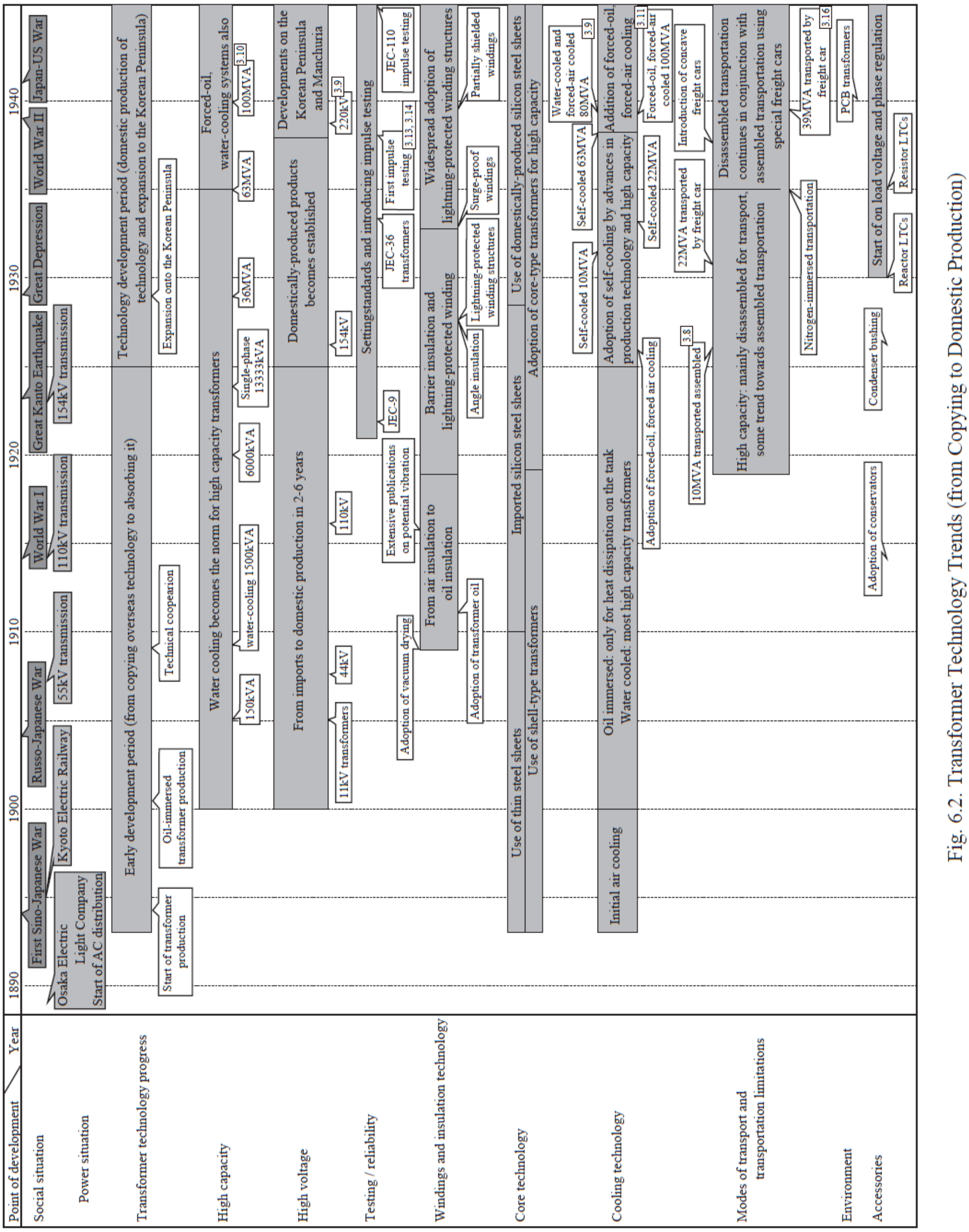


Fig. 6.1. Systematisation of Transformer Technology (from Copying to Domestic Production)

(Fig. 6.1. Systematisation of Transformer Technology (from Copying to Domestic Production))



(Fig. 6.2. Transformer Technology Trends (from Copying to Domestic Production))

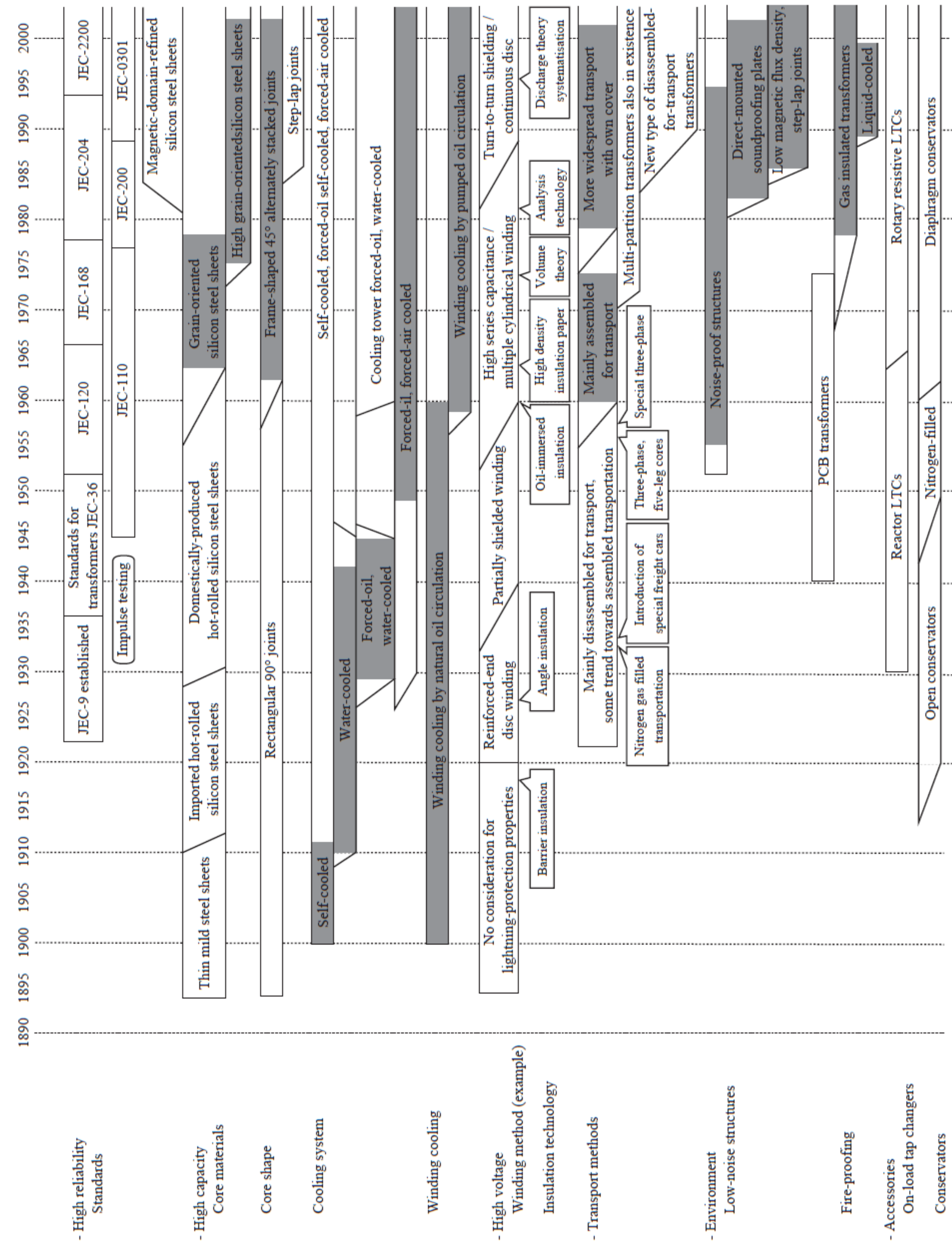


Fig. 6.3. Timewise Trends in Main Technologies

(Fig. 6.3. Timewise Trends in Main Technologies)

Table 6.1. Main Transformer Technologies and Products (pre-1950)

	Pre-1900	1900s	1910s	1920s	1930s	1940s
High reliability					- Potential distribution measurements 1933	
Testing					- Impulse voltage generators 1934 - Impulse testing implemented 1937	
Standards				- JEC-9 electrical equipment standard regulations established 1922 - Transformer standard JES-31 issued 1926	- JEC-36 established 1934 - Wartime standard JEC-36Z issued 1938	- JES on mineral transformer oil issued 1941 - Impulse testing standard JEC-110 issued 1945
High capacity	- Transformer production starts 1893	- Oil-immersed transformer production starts 1900 - 1500kVA transformer manufactured 1909	- Start of use of core-type for high capacity 1919	- First transformer over 10MVA produced 1924		
Core			- Start of use of silicon steel sheets 1910	- Start of domestic production of silicon steel sheets 1922 - Start of use of domestically-produced silicon steel sheets 1928		
Cooling	- Air cooling 1893	- Oil-immersed self-cooling 1900 - Use of water cooling around 1909		- Use of forced-oil, forced-air cooling 1926 - Self-cooling used on high capacity 10MVA 1927	- Forced-oil, water-cooled 30MVA 1930	- First use of banked radiator system 1940 - First use of finned unit-cooler 1941 - First use of unit-cooler 1948
Modes and methods of transport				- 10MVA transported by sea with interior assembled 1926 - 7.5MVA transported in oil 1928	- 22MVA sent by rail immersed in oil 1932 - First use of nitrogen immersed transportation	

					1935 - Concave railcar produced 1936 - Assembled transportation by special railcar 1939	
High voltage						
Winding method				- First use of lightning-protected winding structures 1928	- First use of surge-proof windings 1932 - Start of use of partially-shielded windings 1939	- First use of multiple cylindrical windings 1940 - First use of neutral insulated method 1948
Insulation material			- Start of import and use of transformer oil 1911 - Start of domestic production of transformer oil 1913	- Use of flange collar 1928		
Insulation technology		- Start of use of vacuum drying 1909	- Extensive studies on potential vibration around 1916	- First 154kV produced 1926	- First 220kV 1939	
Environment						
Low-noise structures						
Fire-proofing						- Non-flammable synthetic oil (PCB) transformer 1940
Accessories						
On-load tap changers			- First induced voltage regulator produced 1912		- First on-load voltage regulating transformer 1930 - Resistance-type on-load tap changers introduced 1935	
Conservat			- First use			- First use of

ors			of conservators 1914			nitrogen-filled conservators 1942
Coolers, radiators						
Bushing				- First condenser bushing 1926		
Typical products		- 11kV, 150kVA for Kofu Electric 1905 - 44kV, 1500kVA r for Yokohama Electric 1909	- 66kV, 2500kVA r for Kyushu Hydroelectric 1912 - 500kV testing transformer for the University of Tokyo 1915 - 110kV, 4400kVA for Inawashiro Hydroelectric 1917	- 77kV, 13333kVA r for the Nippon Electric Ozone Substation 1924 - 154kV, 6667kVA for the Nippon Electric Gifu Substation 1926 - 140kV, 22MVA self-cooled for the Showa Electric Yao Substation 1928	- 450kVA LVR for Chugoku Electric Power Company 1930 - 140kV, 39MVA assembled-transported for Tokyo Electric Light Company 1939 - 220kV, 80MVA for Changjin River Hydroelectric 1939	- 230kV, 100MVA for Yalu River Hydroelectric 1940

6.2. Post-War to 1975

(1) 275kV Transformers and Introduction of Overseas Technology

The first post-war technology epoch was the completion of the Kansai Electric Power Company Shin-Hokuriku Trunk Line 275kV power line and the completion of the transformers for that line. These transformers were subject to impulse testing under the new regulations; to achieve this, each company used its accumulation of pre-war technology and also incorporated the latest technology. New technologies included *main-gap-filling insulating structures* and *non-resonant windings (multiple cylindrical windings)* developed in Europe, *form-fit tank structures* and core-erecting equipment. In 1952, technical cooperation with overseas manufacturers resumed, having been suspended during the war, bringing with it a wealth of new overseas technology that had been developed during and since the war. This included a lot of technology still used today; for example, *grain-oriented silicon steel sheets*, *frame-shaped cores*, *vapour-phase-drying*, forced winding cooling and *transposed cables*. The grain-oriented silicon steel sheets developed by US company Armco played a major role in the later downsizing of the core and proved to be very useful in ushering in high capacity transformers. Their magnetic properties were superior to those of the hot-rolled T-grade cores of the time; capable of use at a higher magnetic density, they made it possible to downsize the core in inverse proportion by 1.3/1.7 (around 76%). The transition to grain-oriented silicon steel sheets was complete by around 1962, when a domestic version appeared on the market.

In terms of insulation technology, high series capacitance windings developed in the United Kingdom were soon developed and incorporated into Japanese technology; these were late used as a powerful tool for changing to higher voltage. These windings made particularly well-insulated windings when combined with the newly-developed high-air tight wire insulating paper. Other completely original Japanese windings, such as *damper-shield windings*, were also developed and contributed to the change to higher voltage. By adopting this technology, the 275kV transformer introduced in 1952 could have even more compact insulation in the 1960s. Combining multiple cylindrical windings with transposed cables made it possible to use them as high-voltage windings in high capacity transformers; from the 1960s to the 1970s, the ultra-high-capacity 1000MVA transformer was the prized goal.

(2) High Capacity Substation Transformers and LRT

Increased demand for electricity in the 1950s led to high capacity transformers at primary substations. Assembled transportation by special railcar became the norm, since it meant that these could be installed on site quickly and easily. This was made possible through core materials and structures, as mentioned previously, as well as other the use of three-phase, five-limb cores, the emergence of special freight cars with higher carrying capacity and the development of *special three-phase transformers*. Around the mid-1950s, assembled transportation was carried out for 275kV transformers as well; this was assisted by improvements to lightning-protected winding structures resulting in insulation taking up far less space in the winding. Addoption of graded insulation of the neutral point on the 154kV system cannot be overlooked either. As a result, while pre-war railcar transport limitations had meant the transportation of nothing greater than a 154kV, 39MVA transformer, by 1963 it was possible to transport a 275kV, 300MVA transformer for the Chubu Electric Power Company Nishi-Nagoya Substation.

While it became the norm during this time for distribution transformers to have on-load tap changers, there was a growing demand for them at primary substations as well. The on-load tap changers (LTCs) at the time were mainly the American-style reactor type, although some German-style resistor type ones were also used. Two systems were used concurrently: connecting an on-load voltage regulator in series with the transformer, or using load ratio control transformers (LRTs), with a tap winding inside the transformer itself. However, in the 1960s, there was a growing trend to use LTCs at primary substations with the LTC built into the transformer tank; the demand for LRTs that could be transported together with the main transformer itself grew as the demand for high capacity transformers grew. The reactor type was deemed unsuited to this demand, while the LTC made by the globally-renowned German LTC manufacturer MR was deemed to be the most suited to it. Three transformer manufacturers introduced this product through technical cooperation. Since then, models developed by MR have been the main ones used in Japan.

(3) Changes in Accessories

Water cooling was the main transformer cooling system before the war. In the 1950s, finned air coolers began to be fitted directly onto transformers. These were combined with pumps to form cooling units. Forced cooling systems were introduced, forcing oil directly into the winding from the pump; these later became the norm for high capacity transformers. Coolers first had copper ribbons wrapped around iron pipes; in the 1960s, aluminium coolers appeared with fins extruding from aluminium pipes – these became the norm. However, there was a transition in the 1970s to iron coolers with heat sinks fitted to iron tubes, due to problems with aluminium coolers corroding from salt-air damage, particularly at coastal power stations, as well as the fact that in the event of a transformer fire, the aluminium would weaken with the heat and damage the adjoining banks as well.

When urban underground substations began to be built at the end of the 1950s, a cooling system was developed that had cooling towers in which water would circulate and be cooled by the outside air. This system later became the norm. In 1960, the first 154kV, 100MVA high capacity transformer was introduced to an urban underground substation. Later, in the 1970s, the introduction of the 275kV system in urban centres saw the establishment of 300MVA high capacity transformers. Special three-phase type transformers were adopted for underground substations due to service access limitations, ceiling height limitations and road transport limitations. Various ingenious approaches also had to be used to assemble them.

Self-cooling systems were mainly used on transformers of 50MVA or lower. As their scope of application expanded, the existing oval tube shape used to increase the radiator space factor was replaced by a flat tube shape in the early 1960s. This increased the effectiveness of the fans where fans were used, making it possible to increase the rated capacity of the air-cooled type transformers.

In the 1950s, the existing open-type conservators began to be replaced in standard use by *nitrogen-filled conservators*, which greatly improved the issue of oil oxidation. However, a *diaphragm system* developed in the United States was introduced in the 1960s, using a rubber film to separate the oil and the air. Around the mid-1960s, following domestic production of these rubber films and validation of their transmission properties, the diaphragm system took hold as the norm, contributing greatly to improving installation space and increasing the analytical precision of gas-in-oil analyses, which later became the norm.

(4) Response to Environmental Issues

Let us finally touch on environmental issues. In 1952, the first low-noise-specification transformer was produced for use in an underground urban substation. This was a 15MVA distribution transformer. In 1956, a high-capacity 110MVA transformer was produced for the Tokyo Electric Power Company Toda Substation (Photo 6.1). At the time transformers were not bound by urban noise restrictions and so the demand for low-noise specifications was sporadic. However, there was demand in special circumstances, and low-noise transformers with *soundproofing structures* and transformers with *concrete sound barrier structures* began to appear in the early 1960s. In any case, an awareness of environmental issues can be said to have emerged in the early 1950s.

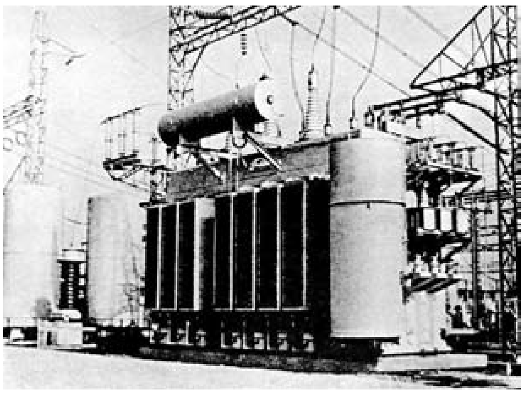


Photo 6.1. The First High-Capacity, Low-Noise Transformer, a 110MVA Transformer for the Tokyo Electric Power Company Toda Substation (1956, made by Toshiba)

Demand for non-flammable transformers at secondary substations in urban basements appeared around the mid-1950s, albeit sporadically. This continued until the 1970s, when a pollution issue with a 60kV, 10MVA *PCB* transformer resulted in the banning of the production or use of PCB transformers.

(5) Breaking Away from Introduced Technology

With the growing demand for electricity in the 1960s, a number of high-capacity thermal power stations were built in various places. Most of the primary equipment, such as power turbines and generators were imported, while the secondary and other lesser equipment was Japanese. Primary transformers, however, were Japanese, because by this time Japanese transformer technology was equal to that from overseas, Japan having actively combined new post-war technology with its pre-war technological capabilities.

The greatest technical challenge in producing transformers for high-capacity thermal power stations was local heating of structural materials due to leakage flux from the winding. For example, the flange joining the upper and lower tanks would heat up, burning the paint. Nobody overseas had enough experience for this issue to be solved through technical cooperation, so Japan had to solve the problem for itself. Improvements were made through trial and error, such as the range and method of attaching the electromagnetic tank shielding. In some cases, other problems occurred, such as a build-up of flammable gas on site. However, the issues were gradually solved, resulting in a store of technology able to be used on higher capacity transformers.

It also became standard practice to transport assembled substation transformers by rail. The insulation had to be compact for the contents of the transformer to fit within the rail transport limitations. This was difficult to achieve with introduced technology, which mainly came from the United States, (as there was a trend towards standardisation and reducing production costs rather than economising materials by compacting), so Japan had to make its own improvements. Thus, independent Japanese technology became established and there was a gradual shift away from technology imported from overseas.

(6) Development of 500kV Transformers

Once the rigorous demand for electricity leading into the 1960s had been met, manufacturers started devoting their efforts to exporting to keep themselves in work. It had been more than ten years since the 275kV supply voltage had been introduced in Japan; 500kV was considered to be the next level of voltage. Manufacturers started testing models in preparation for that.

Various different countries overseas had developed plans for supply voltages of 500kV or 400kV; some of these were being planned by national or state public corporations and offered a chance for unproven manufacturers to make bids. Japanese manufacturers all placed bids and successfully received orders for large quantities of 500kV or 400kV transformers from Canada, the United States, Australia, Mexico and other countries. These transformers had to have *partial discharge test* specifications, which had been brought in after a series of insulation breakdowns in some 500kV transformers, which had passed factory testing, during initial operation in the United States. In those days, factories working with insulation and windings were not partitioned off from outside and people could come in or out without any special precautions. It was difficult to re-educate workers who had been reared in this environment, and it took more than ten years to produce a transformer free of partial discharge. Experienced advice from overseas test witnesses also contributed greatly to the achievement of partial-discharge-free transformers. For example, insulation moisture management and oil treatment technology were based on information they provided, and have become the current norm in Japan. While it took a lot of effort to achieve partial-discharge-free transformers, there was no option to solve it through technical cooperation, so Japan had to solve it on its own.

(7) Systematisation of Technology from Post-War to 1975

The above outline of transformer technology from the post-war period to the domestic development of the 500kV transformer in 1975 and the transition away from overseas technology is shown in Fig. 6.4. Fig. 6.5 shows the timewise trends in the main technologies and products for each of the main transformer issues and also notes the technological development and progress of the period. Table 6.2 shows the development period for the main technologies and products.

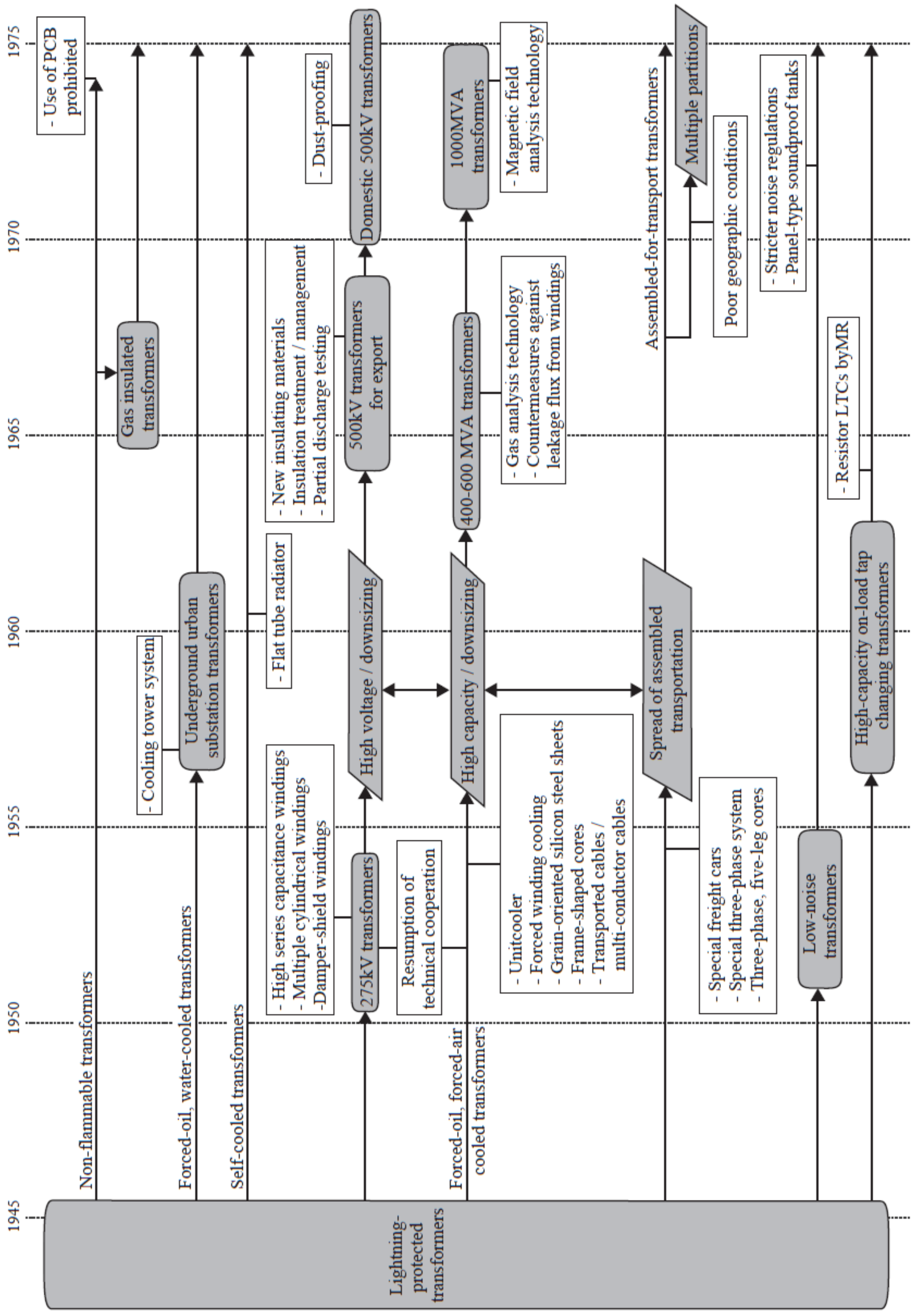
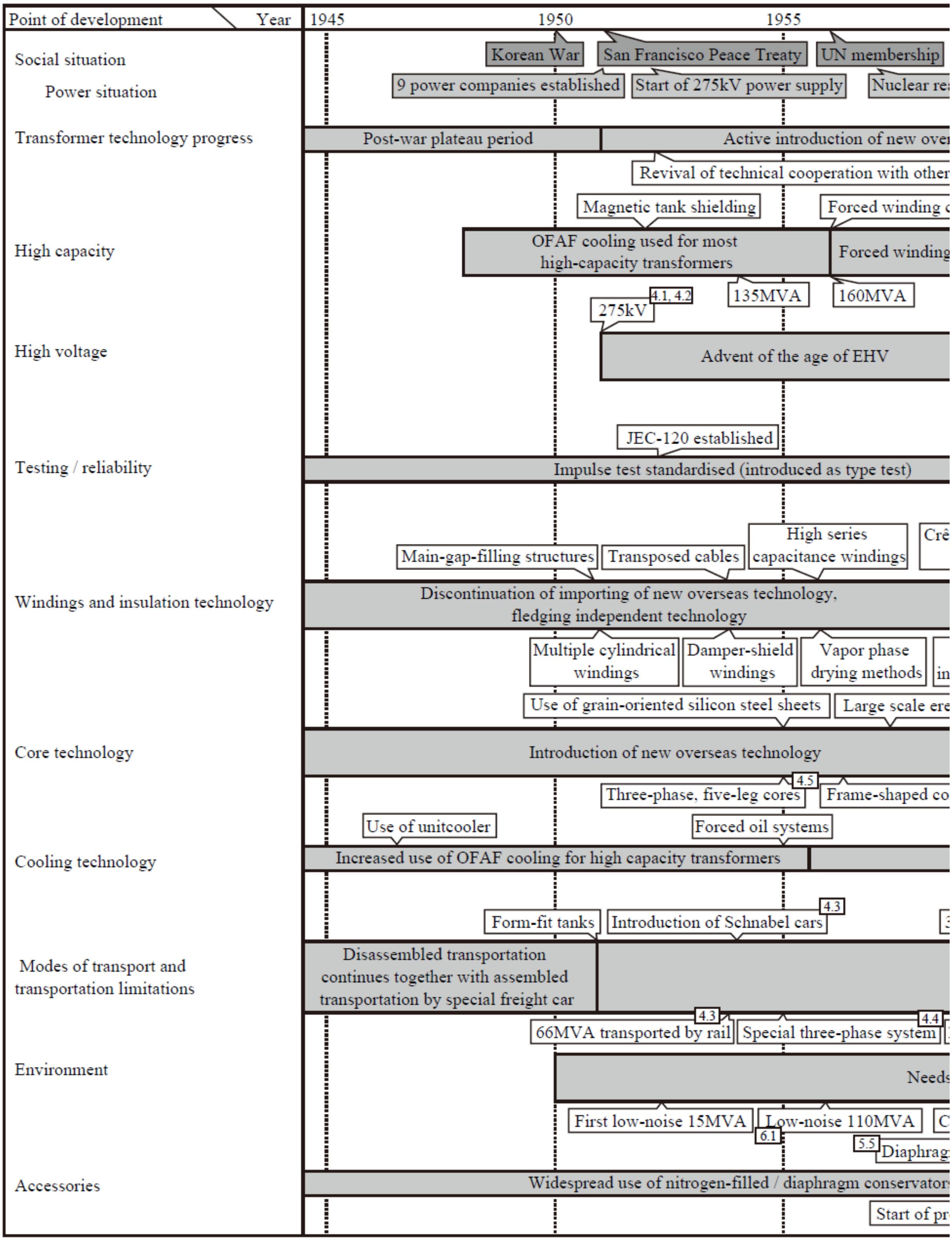
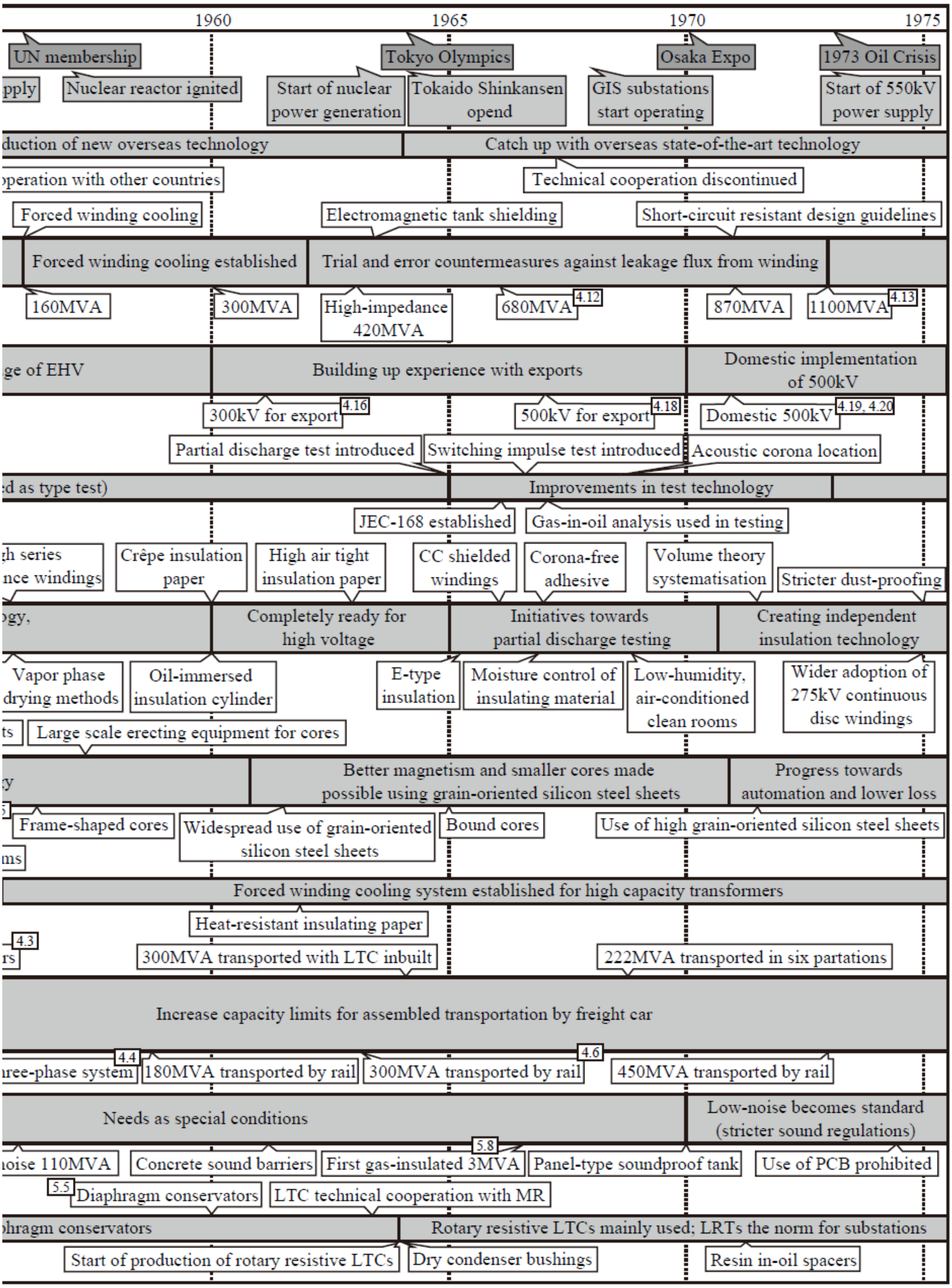


Fig. 6.4. Systematisation of Transformer Technology (Breaking Away from Overseas Technology)

(Fig. 6.4. Systematisation of Transformer Technology (Breaking Away from Overseas Technology))



(Fig. 6.5. Trends in Transformer Technology (Breaking Away from Overseas Technology) 1of2)



(Fig. 6.5. Trends in Transformer Technology (Breaking Away from Overseas Technology) 2of2)

Table 6.2. Main Transformer Technologies and Products (1950 onwards)

	1950s	1960s	1970s	1980s	1990s
High reliability			- Adoption of tank flange reinforcing structures 1974	- Establishment of seismicproof design for transformer bushing 1983	- Transformer deterioration diagnosis guidelines 1999
Testing		- Partial discharge test introduced 1965 - Switching impulse test introduced 1966 - Gas-in-oil analysis used in testing 1967 - Acoustic corona location technology established 1967	- Development of automatic gas analysis equipment 1977		- Gas-in-oil analysis diagnosis guidelines 1999 - Methods for managing flow electrification 1999
Standards	- JEC-120 established 1952	- JEC-168 established 1966	- JEC-204 established 1978 - Regulations for seismicproof transformer design 1978	- Gas-in-oil analysis maintenance criteria established 1981	- JEC-2200 established 1995
High capacity	- Use of magnetic tank shielding 1952	- Use of electromagnetic tank shielding 1963			
Core	- First use of grain-oriented silicon steel sheets 1955 - First use of three-phase, five-leg cores 1955 - First use of frame-shaped cores 1956 - Core-erecting equipment established 1958 - Core plate processing	- Use of bound cores 1965	- First use of high grain-oriented silicon steel sheets 1972 - No-bake cores become the norm 1975	- GEORG's automatic core cutting machine introduced 1980 - First use of magnetic-domain-refined silicon steel sheets 1982 - First use of step-lap cores 1984 - First use of core legs automatic loading equipment 1985	

	line constructed 1959				
Cooling	- First use of forced winding cooling 1956 - Development of cooling tower water cooling system 1957				
Modes and methods of transport	- First use of form-fit tanks 1951 - Tank transported on its side 1951 - First use of special three-phase transformers 1955 - Schnabel cars produced 1955 - First use of a floating crane 1956	- Transformers with inbuilt LTCs become the norm 1963 - Transformer built with six partitions for transportation 1968	- Air pallet transport method introduced 1975 - Transportation of 500kV transformers with main cover on becomes the norm 1977 - Site installation transportation using air pallet bearings 1978	- First use of new disassembled-for-transport transformers 1984	
High voltage		- First 500kV transformer produced 1967	- 500kV transformer produced for the domestic market 1971 - UHV test transformers completed 1978	- UHV technology applied to transformers of 500kV and under 1981	- UHV field testing equipment completed 1993
Winding method	- Use of multiple cylindrical windings for transformers 1951 - First use of damper shield windings 1954 - First use of transposed cables and multi-conductor cables 1954	- First use of CC shielded windings 1966 - Large-scale vertical winding machines introduced 1966	- First use of heat-sealed transposed cables 1975 - Wider use of continuous disc windings for EHV 1975		

	- First use of high series capacitance windings 1956				
Insulation material		- First use of oil-immersed resin adhesive insulation cylinders 1960 - First use of crêpe insulation paper 1960 - First use of paper wound soft copper and flexible copper wires 1960 - First use of heat-resistant insulation paper 1962	- Use of high density pressboard 1972 - New insulating materials become the norm 1975	- First use of BTA-added transformer oil 1980 - First use of low-dielectric-constant pressboard 1989	
Insulation technology	- First 275kV transformer produced 1951 - First use of main-gap-filling structures 1951 - First use of induction heating drying method 1951 - First use of electrostatic shielding systems 1951 - First use of vapor phase drying method 1956	- First use of hourglass insulation 1962 - First use of E-type insulation 1966 - Moisture control of insulation material introduced 1967 - Low-humidity, air-conditioned clean rooms introduced 1967	- Volume theory systematisation 1971 - Flow electrification phenomenon solved, prevention technology established 1976 - Magnetic field analysis and potential vibration analysis technology established 1976	- Study on various properties of composite insulation 1980 - ZnO arresters used in oil to protect tap windings 1982	
Environment					
Low-noise structures	- Low-noise transformers produced 1952 - Low-noise transformers	- Low-noise transformers produced with concrete sound	- Panel-type soundproof tanks used 1970 - Noise control guidelines	- First use of highly effective soundproof panels 1981 - Development of low-noise	

	produced with sound barrier structures 1957	barriers 1961	issued 1977	high-capacity transformers with no soundproof panels 1984	
Fire-proofing		- First gas insulated transformers produced 1967	- Gas insulated transformers used PET film produced 1978	- Liquid-cooled gas-insulated, high capacity transformers produced 1989	- Gas-cooled, gas-insulated high capacity transformers completed 1994
Accessories					
On-load tap changers		- First use of hot line oil purifiers 1960 - LTC technical cooperation begins with German company MR 1963		- First use of MR new series LTCs 1980 - First use of gas-insulated LTCs 1982 - High-capacity, gas-insulated LTCs completed 1989	
Conservators		- First use of diaphragm conservators 1960			
Coolers, radiators		- First use of double-tube water cooling 1964	- Use of highly efficient FRP fan coolers 1979	- Development of variable speed cooler control 1982	
Bushing		- Use of 275kV cable-connected transformers 1960 - Dry condenser bushing production begins 1964		- First use of pressboard in-oil spacers 1984	
Typical products	- 275kV, 99MVA transformer for the Kansai Electric Power Company Hirakata Substation 1951 - 110MVA low-noise transformer for the	- 154kV, 100MVA underground transformer for the Tokyo Electric Power Company Chiyoda Substation 1960 - 275kV, 300MVA transformer	- 500kV, 333.3MVA transformers for the Tokyo Electric Power Company Shin-Koga and Boso Substations 1971 - 275kV, 1100MVA transformer for the Tokyo Electric Power	- 765kV, 800/3MVA transformer for Venezuela 1982 - 275kV, 300MVA new disassembled-transport-type transformer for the Kansai Electric Power Company Kobe Substation 1984 - 154kV, 200MVA liquid-cooled,	- 275kV, 300MVA liquid-cooled, gas-insulated transformer 1990 - 300MVA, 60dB transformer with no soundproof panel for the Tohoku Electric Power Company Ishinomaki Substation 1992 - UHVdemonstration testing transformer for the Tokyo Electric Power Company

	Tokyo Electric Power Company Toda Substation 1956 - 154kV, 75MVA transformer with inbuilt LTC for the Tokyo Electric Power Company Kuramae Substation 1959 - 275kV, 270MVA transformer for the Chubu Electric Power Company Shin-Nagoya Power Station 1959 - 275kV, 264MVA transformer transported assembled for the Electric Power Development Company Nishi-Tokyo Substation 1959	with inbuilt LTC for the Tokyo Electric Power Company Higashi-Tokyo Substation 1965 - 275kV, 680MVA transformer for the Tokyo Electric Power Company Anegasaki Power Station 1966 - 500kV, 200MVA transformer for Canada 1967 - 66kV, 3MVA gas-insulated transformer for Daiichi Life 1967	Company Kashima Power Station 1973 - 275kV, 450MVA transformer transported by rail for the Chubu Electric Power Company Sunen Substation 1974 - 500kV, 1100MVA transformer for the Tokyo Electric Power Company Sodegaura Power Station 1974 - 66kV, 10MVA gas-insulated transformer for the Japanese National Railways Joetsu Shinkansen 1978	gas-insulated transformer for the Tokyo Electric Power Company Asahi Substation 1989	Shin-Haruna Substation 1993 - 275kV, 300MVA gas-cooled/insulated transformer for the Tokyo Electric Power Company Higashi-Shinjuku Substation 1994 - 500kV, 100MVA new disassembled-transport-type transformer for the Chubu Electric Power Company Aichi Power Station 1994

6.3. Development of Independent Technology since 1975

(1) Overcoming Flow Electrification and UHV Technology

As discussed in the previous section, Japanese technology capabilities rose swiftly to meet the need to develop technology that addressed the major issues of high voltage and high capacity during this period.

However, amidst this, there were issues with insulation breakdown due to flow electrification in the early domestic 500kV transformers. This was caused by the design of the oil channel, based on superficial trust in imported technology rather than independent ground-up investigation when producing high-capacity, high-voltage transformers, which went beyond the scope of anyone's previous experience. It may sound like an excuse, but at the time no technicians anywhere in the world were aware of the issues with frictional static electricity within transformer: a fact that those who first caused the problem may take some comfort in. It took over two years of systematic investigation to solve this issue and propose countermeasures. A keen sense of the importance of back-to-basics development was quickly adopted during this process, but the lesson learnt ensured later success in developing UHV transformers and developing and implementing the world's first high-capacity, gas-insulated transformers.

This period is an age of major developments in Japanese transformer technology. In the late 1970s, research was carried out on in-oil electrical discharge mechanisms, going back to the basics of oil insulation in response to the severe rail transport limitations unique to Japan. This resulted in the successful development of compact, reliable, highly-insulated structures, which, combined with the appropriate configuration of insulation, made it possible to produce UHV transformers with twice the voltage of the existing 500kV transformers while keeping within the same transportation limitations. With UHV implementation delayed, this technology was put to use in transformers of 500kV and under, contributing to a major reduction in the resources used on these transformers. In light of the insulation breakdowns with 500kV transformers at this time and power companies focusing more on reliability given the demand for a reliable power system in a computerised society, there was a growing demand for transformers to be transported with the main cover in place, despite the first 500kV transformers having usually been transported with a temporary transport cover on, which was then replaced with the main cover. Meanwhile, rationalisation of the railway companies meant that special allowances were no longer made for products such as transformers being transported under special limitations, resulting in more limited transportation conditions with smaller dimensions than before. To meet these requirements, the aforementioned insulation rationalisation was used to reduce dimensions of the transformer; transportation with the main cover on then became the norm.

(2) Development of Underground Substations

With the increase in urban electricity consumption, extremely high voltage power began to be brought in from outer lines into city centres and then supplied to secondary substations. Power cables were used to convey power into city centres, eventually forming networks of large-scale substations furnished with 275kV, 300MVA underground transformers. Gas-insulated switchgear contributed greatly to the spread of these underground substations. A special three-phase format was the norm for transformers in these underground substations. However, special three-phase transformers had less scope for expansion than normal in the event of an internal insulation breakdown. The larger the network, the larger the fault current and there was concern that oil would leak from the weakest point – the tank flange – and cause a fire before the fault current could be isolated. Countermeasures were investigated, with power companies and manufacturers jointly deciding on disaster-proof structures for underground substation transformers and making appropriate alterations to existing transformers. Meanwhile, research continued into the 1980s on the possibility of a non-flammable, high-capacity, gas-insulated transformer and various methods were developed.

As cable networks expanded, there was an increasing demand for high-capacity *shunt reactors* to compensate for leading currents caused by the charge capacity of the cable during light loads at night. These were first used for compensation in tertiary transformer circuits, but later 150MVA high-capacity versions came to be in standard demand instead of directly connecting to the 275kV system due to their efficiency.

(3) Development of Gas-Insulated Transformers

The impulse properties of gas-insulated transformers greatly improved with the use of film insulation and they were put to practical use from 1978, mainly in underground substations for industrial or transport-related uses. A major factor was the compact configuration of substation facilities made possible through the standardisation of GIS in particular. Later, gas LTCs were also developed and used in power companies' secondary substations. This required a capacity increase from the previous 10MVA to 30MVA as well as self-cooled transformers; these hurdles were cleared with the use of more effective winding cooling and high thermal insulation. While low-pressure gas-insulated transformers with a gauged pressure of 0.11-0.14MPa are not subject to the regulations on high-gas-pressure vesells (maximum pressure of at least 0.2MPa) and are currently used for low capacity uses, they are being manufactured with increasing capacity, with a 161kV, 68MVA transformer for the Tohoku Electric Power Company Yanaizu-Nishiyama Geothermal Power Station produced in 1994 as having the highest capacity thus far (Photo 6.2).

Photo 6.2. A 161kV, 68MVA, Low-Pressure Gas-Insulated Transformer for the Tohoku Electric Power Company Yanaizu-Nishiyama Geothermal Power Station (1994, made by Toshiba)

High-capacity gas-insulated transformers first started being developed in the United States. Progress had been made in the early 1980s to develop and implement a 300MVA transformer, but the Reagan administration suspended the project as part of reducing public finance under the "limited government" slogan. Triggered by this project, plans were made in Japan to develop a gas-insulated transformer as a means of disaster prevention in underground substations. At the time, it was thought difficult to cool a high-capacity transformer using gas alone, so *perfluorocarbons*, used in computers, were proposed as the cooling medium. Various ideas were drafted using this medium to cool the heat generated by the windings and core. In Japan, Mitsubishi, Toshiba and Hitachi each developed their own methods. In 1989, Toshiba successfully implemented the world's first 200MVA transformer; in 1990, each company had successfully developed 275kV, 300MVA or 250MVA transformers. While these developments were simpler in structure than the existing transformers that used oil for insulation and cooling, there were a number of problems in partitioning the SF_6 gas used for insulation from the perfluorocarbons used for cooling, meaning development and testing took a long time. However, the companies each demonstrated their technical capabilities to overcome these difficulties and eventually come up with a product. The companies put a lot of effort into long-term reliability testing, since these structures had no proven track record.

However, the future of these transformers was concerning. Despite being of comparable product design with the existing oil-immersed transformers, they were expected to cost over twice as much, as different materials were used for the insulation and the cooling and the cooling in particular was expensive. Power companies could not be expected to adopt these for the disaster-prevention benefits alone. However, this led to the development of high-pressure gas transformers, the development of blowers that could be used with high gas pressure, the development of PET and other insulation materials with better heat-resistant properties and the development of technology to keep temperature distribution within windings as uniform as possible by analysing gas flow within windings by computer and creating optimal channel structures. This made it potentially possible to adequately handle a significant amount of heat using gas alone, which, following testing on a full-scale model, led to the production of a high-capacity gas-cooled transformer. The first such transformer was a 275kV, 300MVA transformer produced by Toshiba in 1994 for the Tokyo Electric Power Company Higashi-Shinjuku Substation. This development virtually offset the added cost compared to an oil-immersed transformer against the cost of disaster prevention with the added benefit of a greater degree of freedom in the positioning of the transformer and GIS. These were deemed suitable to replace oil-immersed transformers in underground substations and they later gained more widespread use.

Gas-insulated transformers were higher priced than oil-immersed transformers due to the comparatively high cost of the materials while offering no advantage over oil for cooling. The cheaper oil-immersed transformers were far more common around the world. There is a demand for gas-insulated transformers in densely populated cities in China, Hong Kong, Taiwan and other places in Asia, and while Japan is currently the only country with the technological capabilities to supply these, it is expected that joint ventures will begin production before long. However, this is purely for transformers of 50MVA or less; there is presently no demand for high-capacity transformers, although a recent decision to use gas-insulated transformers in underground substations in parks in Australia resulted in an order from TMT&D for a 345kV, 400MVA transformer in 2003.

(4) Transformers for UHV Demonstration Testing

While the implementation of *UHV transformers* was postponed, development resumed in the 1990s and early 2000s, at the sudden emergence of a proposal by Tokyo Electric Power Company to commence UHV operation. Given the strange problem of flow electrification that occurred with the initial 500kV operation, Hitachi, Toshiba and Mitsubishi produced one phase each of an actual transformer based on the specifications for the expected rated values and Tokyo Electric Power Company scheduled two years of demonstration testing of that transformer at the Shin-Haruna Substation, in order to test whether or not some new problem would arise. Before producing the test transformer, a half-phase prototype test transformer was produced to test for any issues and to test for insulation limits. The two years of demonstration testing have been prolonged, with testing still being carried out. During this time, new problems have occurred, meaning that the demonstration testing has been worthwhile. Starting UHV operation has been a huge dream for transformer engineers for many years, but even now in the 21st century there is little prospect of it coming true as yet.

(5) DC Conversion Transformers

DC transmission in Japan started out in the form of frequency conversion for power interchange between 50Hz and 60Hz zones. It began in 1964 with a conversion transformer for the Electric Power Development Company Sakuma Frequency Converter Station made by Mitsubishi using Swedish-made mercury arc valves. Later transformers had thyristor valves instead of mercury arc valves. Following the development and testing of domestically-produced valves, in 1977, the Tokyo Electric Power Company Shin-Shinano Converter Station became the first thyristor converter station. Toshiba and Hitachi shared the production of the 50Hz and 60Hz equipment for this converter station, likewise the transformers.

The first DC transmission in Japan started in 1979 on the Hokkaido-Honshu connection. The transformers operated on a DC voltage of ±125kV, about the same as the Shin-Shinano transformer. At the second phase, the DC voltage was raised to ±250kV and operated commenced the following year, with around 600MW connecting Honshu and Hokkaido. In 1999, DC transmission between Shikoku and the Kii Peninsula started as a result of joint development between Shikoku Electric Power Company, Electric Power Development Company and Kansai Electric Power Company. Operating at ±250kV at the first stage, plans are in place to raise this to ±500kV at the second stage. Some of the equipment is already ready for 500kV use. Before this equipment was manufactured, tests were carried out to check for issues with DC insulation, including model testing and long-term reliability checks by power companies.

(6) Low-Loss Transformers

While the new technologies of UHV, gas-insulated transformers and DC transmission were drawing attention, ordinary transformers were also undergoing changes from the 1980s onwards.

In the 1980s, as the domestic market moved into a period of long-term low growth, more attention began to be drawn to loss, previously not considered to be an issue. Competition ensued to reduce loss. When applying UHV technology to transformers of 500kV and less, the existing high series capacitance windings were largely replaced by continuous disc windings, which used transposed cables or other multi-conductor cables to reduce the winding eddy current. This was able to more than halve the eddy current loss, which accounted for as much as 30% of the total loss in high-capacity transformers. Other improvements included the use of the newly-developed low-loss silicon steel sheets as a core material and of step-lap joints as a core structure, which allowed a smooth flow of magnetic flux across the joint. The reduction in core materials by adopting UHV technology meant a reduction in core loss, more than halving the amount of loss from the 1960s. While previous 500kV transformers had had a two-limb parallel winding structure, the adoption of UHV technology made it possible to reduce this to one limb, thereby making a significant reduction in loss through a significant reduction in materials used.

(7) Low-Noise Transformers

In addition to low-loss transformers, low-noise transformers were another distinctive technology of this period. Transformer noise reduction was becoming common for primary substation transformers as urban noise restrictions tightened in the 1970s, but as the transition of substations to GIS systems made them far quieter than the existing air-insulated substations, new noise restrictions that restricted noise levels at the boundary line demanded lower noise levels than before. In the 1980s, there was a growing trend to keep onsite work as simple as possible and a demand to simplify soundproofing structures. The use of high grain-oriented silicon steel sheets as well as step-lap joints was expected to dramatically reduce noise levels, while a simple sound-proofing structure combining this with reduced magnetic flux density made it possible to achieve noise levels of 60dB even for high-capacity transformers, thus gradually reducing the size of these formerly large sound-proofing structures.

(8) From Partitioned Transportation to Disassembled Transportation

From the 1970s onwards, high-capacity pumped storage power stations began to be constructed in various places; the main issue with these was transportation of equipment, due to geographic constraints. This was a time when transformer reliability was highly emphasised. Transformers could no longer be transported disassembled as they were in the past; increasing demand for them to be transported in their factory-tested condition with the factory product reproduced on site meant an increasing number of cases of increasing numbers of transformer partitions. At the same time, various policies, such as limitations on freight transportation routes, stricter limitations on transportation dimensions and mass, and consolidation of freight stations, appeared as a result of the rationalisation of railroad freight handling, followed by the privatisation of Japan National Railways. An increasing number of substations were located in mountainous areas far from urban centres. Accordingly, transportation also added to the cost, in some cases even amounting to more than 20% of the overall cost, making some kind of solution necessary.Kansai Electric Power Company and Mitsubishi Electric proposed a new disassembled-for-transport method, which was trialled on a 300MVA transformer in 1984. This method involved packing the coils together in film using a structure that prevented moisture absorption during disassembly and onsite reassembly, thereby omitting any onsite drying. A new core structure and onsite assembly conditions equal to those at the factory provided a structure and working system that showed concern for power companies' emphasis on reliability. This move was later taken up by other power companies and manufacturers, who worked on new core structures, made improvements to dustproof working chambers, investigated the necessity of onsite field testing as well as what should be tested, and also brought out testing equipment, resulting in more widespread adoption. While the added complexity of the main structure and the increased time for disassembly and reassembly meant increased cost, there were also advantages, including a dramatic reduction in transport costs, an economising of resources by having three phases in one structure, reduced installation space and reduced loss. This new disassembled-for-transport system is likely to increase in use in future.

(9) Life Expectancy and Prolonging Lifespan

In the 1990s, there was a slump in the demand for electricity following the burst of the bubble economy. With the liberalisation of the electricity market, there was a movement to control costs, and power companies starting sharply reducing their capital expenditure. A growing number of transformers produced post-war also needed to be updated as they were coming to the end of their lifespan. As a result, companies started examining the degree of deterioration on these transformers to gain an accurate understanding of the lifespan of the transformer. The lifespan of the transformer was estimated through the decrease in mechanical strength of the insulating material used due to thermal ageing and the consequent increased possibility of internal insulation failure from a short-circuit current during an external accident. Generally, a transformer had reached its lifespan when the strength of the insulating paper reached one quarter of its original strength. Nuclear power transformers used for base load power generation have a higher load factor; investment is going in to updating the primary ones with the idea that they will last for 60 years. Lately, many transformers that have been in operation for more than 30 years are having their coils replaced.

However, substations transformers have a light load factor, since Japan has put a lot of capital investment into these to ensure power reliability. The load factor also changes at night, which drops the average load factor by 50%. Accordingly, there has been no deterioration despite having been used for more than the generally expected lifespan of 30 years and there is no pressing need to update them. This has meant that there will be a steadily decreasing demand for transformers, with transformer manufacturers having to merge and plan for how to survive in future. This trend has been happening for more than 20 years in the West and is increasingly becoming a reality in Japan as well.

(10) Systematisation of Technology from 1975 Onwards

Looking back at this period, we see that it started out with flow electrification incidents. By overcoming this issue, Japan embarked on the road to developing its own technology and became completely independent from overseas technology. It achieved some notable results, establishing UHV technology and successfully producing the world's first high-capacity gas-insulated transformer. This was also a time for companies to distinguish themselves from others by developing new technologies for existing products in areas such as low loss, low noise or simplicity of transportation. The long-term slump in the economy since the 1990s meant a decrease in new technology developments; as projects continue to be curtailed, there is concern transformer engineers will disperse and the technology will go into decline.

Fig. 6.6 shows the progress of technology, while Fig. 6.7 shows the trends in the major technologies and products.

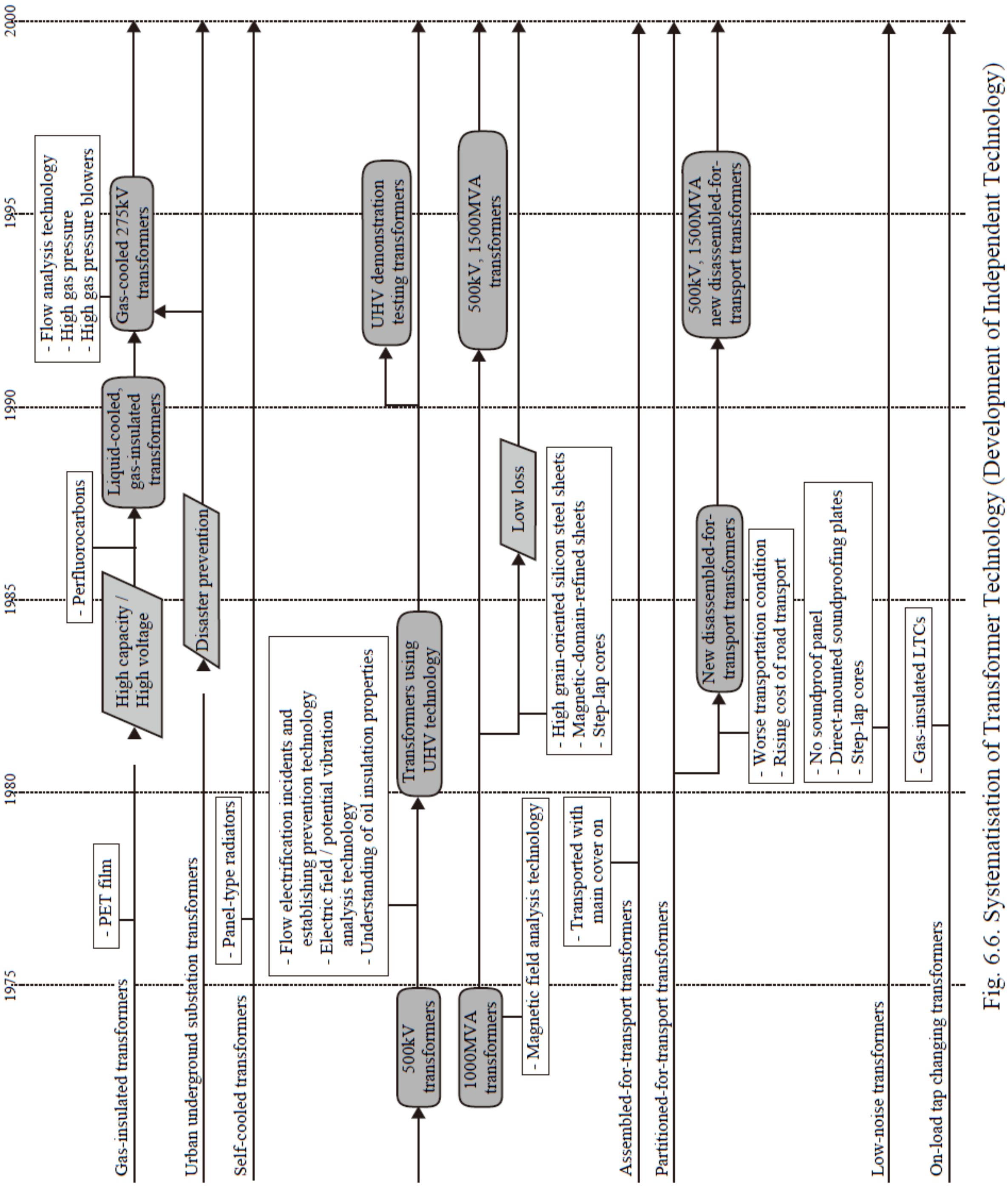
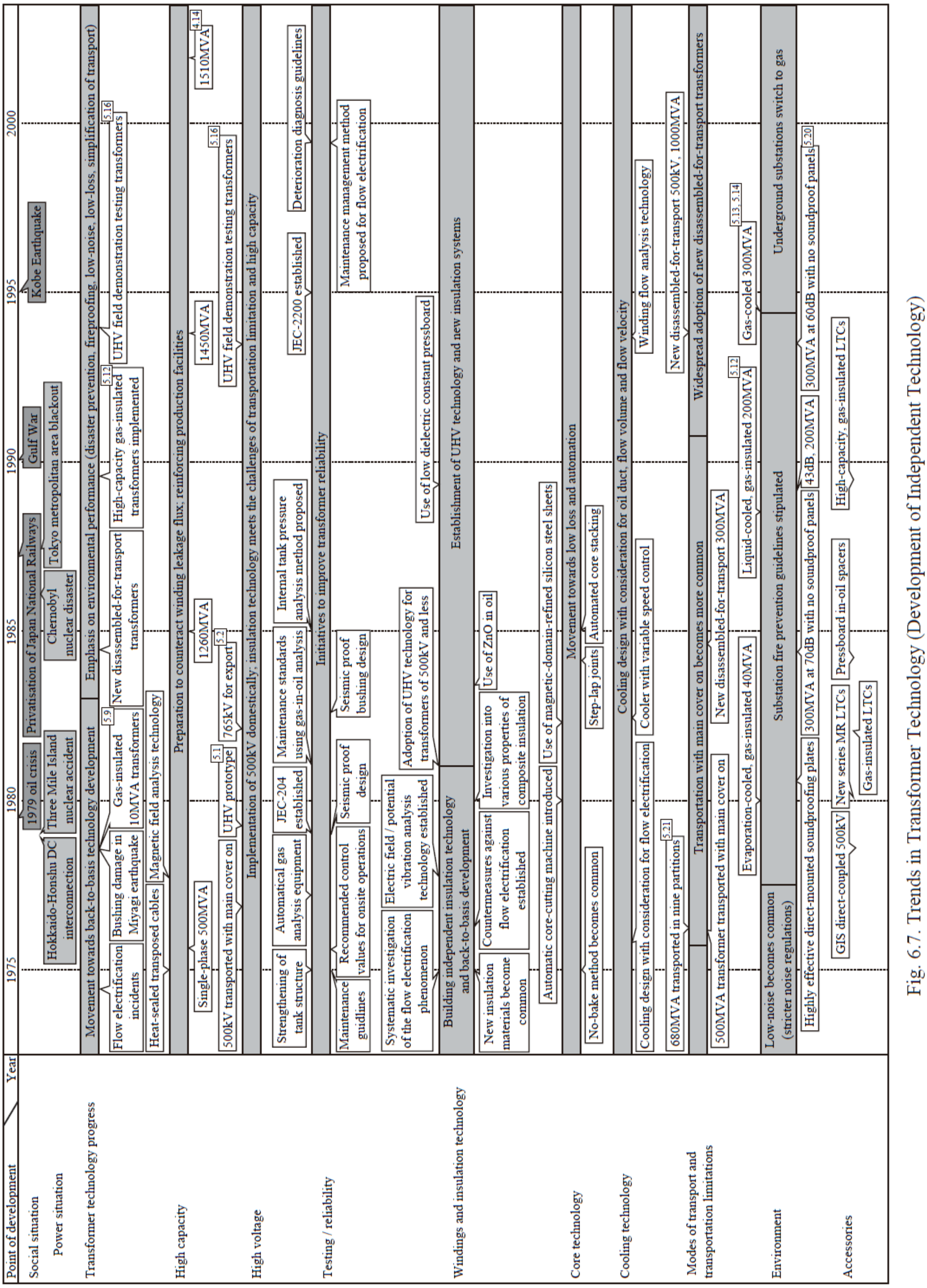


Fig. 6.6. Systematisation of Transformer Technology (Development of Independent Technology)

(Fig. 6.6. Systematisation of Transformer Technology (Development of Independent Technology))



(Fig. 6.7. Trends in Transformer Technology (Development of Independent Technology))

6.4. Characteristics of Japanese Transformer Technology

Finally, let us discuss the characteristics of Japanese transformer technology. Much of the Japanese transformer technology after the war was developed from American technology introduced through technical cooperation. However, as the economy developed, it became difficult to simply adopt American designs due to differences in design philosophy resulting from differences in industrial structure. Specifically, the high cost of labour in the United States meant that designs were as standardised as possible with simple structures, with priority given to reducing labour hours rather than the cost of materials. In Japan, however, materials were expensive but labour was cheap, so designs tended to focus on bringing down the cost of materials, even if it meant more labour hours. Accordingly, in developing the 500kV transformer as capacity and voltage increased, designs tended to be compact with complex structures due to the greater rail transport limitations in Japan than in the United States; according to this design philosophy, products could not have any room to spare. Thus, the primary feature of Japanese transformers is the tendency towards compact design due to the unique size and mass restrictions for rail transport. This also gave rise to the idea of special three-phase systems. The next feature is the globally-unrivalled factories with their thorough quality control not only in design but also in production, such as dust-proofing, due to the strong demand from power companies for transformer reliability, in turn stemming from for a strong demand from society for a stable power supply. One example is Japan's specified acceptable levels for partial discharge testing, which are far stricter than the global standard. From the same perspective, Japan also has far stricter requirements for environmental performance than other countries. Low-noise transformers have been the norm since noise regulations were tightened in the 1970s, when transformer substations began to be placed closer to residential areas. The use of GIS at substations has reduced the level of noise at the boundary, resulting in even stricter low-noise specifications for transformers. Gas is also being adopted for substations in urban basements or at public facilities such as transport stations in order to prevent any fires or oil flow out caused by internal faults in the transformer. While gas insulation is possible for high-capacity transformers, this technology exists only in Japan. The fourth feature is that most of the electricity consumption is in cities, requiring high-capacity, high-voltage transmission from distant power sources. For this reason, Japan produces the world's highest-capacity single-unit transformers, capable of 1500MVA, for its power stations, while transformers with bank capacity of 1000-1500MVA are widely used for substations. Japan's wealth of independent technology has contributed greatly to overcoming the technical issues with high capacity and carrying out preventive maintenance using gas-in-oil analysis. Demonstration testing is being carried out with the aim of implementing high voltage of 1000kV; Japan is completely prepared to put this into operation at any time. Japan can be proud to have carried out all kinds of reliability tests and established the technology for 1000kV UHV transmission in particular, despite having stricter transportation limitations than other countries.

7. Transformer Preservation

With regard to the status of power transformer preservation, the author conducted a survey to examine the current state of transformers manufactured by Hitachi, Toshiba, Mitsubishi, Fuji and Meidensha that had had new technologies applied to them or were record-breaking products for these companies. The author compiled survey data on products still existing in Japan, excluding those exported overseas. There was a total of 128 data items. While transformers are generally said to have a lifespan of 30 years, they are actually used for 40-50 years. Accordingly, the oldest transformers currently being used in Japan are from the early 1950s; any older transformers within the range investigated had all been scrapped. However, two items referred to transformers manufactured in 1910 that have been kept as memorabilia at the factory once no longer used by the client. Products of this age are relatively small and possible to store; later products were too big to store and have all been scrapped. The reality is that at the time, there was no thought to preserve them. Of the 128 items, 33 products thought by the author to be epoch-making products in terms of technology were selected as candidates for registration, along with an original product control ledger by test number, started in 1905, and an original test report taken after the Great Kanto Earthquake. Table 7.1 shows an overview of the candidate products for registration.

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Table 7.1. Overview of Candidate Transformers for Registration

No.	Name	Format	Location	Manufacturer	Year	Comments
1	Transformer test number ledger	Actual item	TMT&D Hamakawasaki Office	Shibaura Engineering Works	1905	An early record ledger that started managing transformers by their test numbers
2	Transformer test report	Actual item	TMT&D Hamakawasaki Office	Shibaura Engineering Works	1923	The oldest extant record of a transformer test report
3	13.2kV, 100kVA extra-high voltage transformer	Actual item	Tokyo Electric Power Company Electric Power Historical Museum	Shibaura Engineering Works	1910	The oldest extant extra-high voltage transformer
4	5kVA,single-phase transformer	Actual item	Hitachi, Ltd. Kokubu Factory	Hitachi, Ltd.	1910	The first transformer by Hitachi, Ltd.
5	Special three-phase, 275kV, 93MVA transformer	Actual item	Electric Power Development Company Sakuma Hydroelectric Power Station	Mitsubishi Electric Corporation	1955	The first transformer to use special three-phase and the oldest extant 275kV transformer
6	Special three-phase, 275kV, 133MVA underground power station transformer	Actual item	Electric Power Development Company Okutadami Hydroelectric Power Station	Tokyo Shibaura Electric Co., Ltd.	1960	Used in an early underground power station with a 275kV cable direct connection structure
7	275kV, 300MVA, on-load tap changing transformer	Actual item	Tokyo Electric Power Company Kita-Tokyo Substation	Mitsubishi Electric Corporation	1962	The highest capacity substation LRT and the first transformer to use a MR LTC
8	Three-phase, 275kVA, 680MVA transformer	Actual item	Tokyo Electric Power Company Anegasaki Thermal Power Station	Tokyo Shibaura Electric Co., Ltd.	1966	The highest capacity transformer at the time
9	45dB super-low-noise 180MVA transformer	Actual item	Kyushu Electric Power Company Nishi-Fukuoka Substation	Meidensha	1967	The first domestically-produced 45dB low-noise, high-capacity transformer
10	275kV, 300MVA underground substation transformer	Actual item	Tokyo Electric Power Company Jonan Substation	Tokyo Shibaura Electric Co., Ltd.	1969	The first 275kV, high-capacity underground substation transformer
11	The first domestically-produced single-phase, 500kV, 1000/3MVA auto-transformer	Actual item	Tokyo Electric Power Company Shin-koga Substation	Tokyo Shibaura Electric Co., Ltd.	1971	Japan's first commercial 500kV transformer
12	Three-phase 275kV, 1100MVA transformer	Actual item	Tokyo Electric Power Company Kashima Thermal	Tokyo Shibaura Electric	1973	The first 1000MVA ultra-high capacity transformer

			Power Station	Co., Ltd.		
13	Assembled-for-transport 275kVA, 450MVA on-load tap changing transformer	Actual item	Chubu Electric Power Company Sunen Substation	Tokyo Shibaura Electric Co., Ltd.	1974	The highest-capacity transformer to be transported by freight car with three phases in one unit
14	Forced-gas, forced-air cooled, 66kV, 10MVA gas-insulated transformer	Actual item	East Japan Railway Company Kita-Nagaoka Laboratory	Meidensha	1978	The first gas-insulated transformer with insulating film
15	UHV prototype transformer	Actual item	TMT&D Hama-Kawasaki Office	Tokyo Shibaura Electric Co., Ltd.	1979	A prototype transformer capable of UHV within rail transportation limitations
16	Single-phase, 500kV, 1500/3MVA auto-transformer	Actual item	Chubu Electric Power Company Shin-Mikawa Substation	Hitachi, Ltd.	1982	UHV technology applied to a 500kV transformer
17	Gas-insulated, on-load tap changing, 66kV, 11MVA transformer	Actual item	Sapporo City Transportation Bureau Asabu Tetsukita Substation	Fuji Electric Co., Ltd.	1982	The first gas-insulated transformer equipped with a VCB LTC
18	Evaporation-cooled, 77kV, 20MVA, gas-insulated transformer	Actual item	Kansai Electric Power Company Nishi-Shirahama Substation	Mitsubishi Electric Corporation	1984	The first forerunner of liquid-cooled, gas-insulated transformers
19	Single-phase 500kV, 1000/3MVA transformer	Actual item	Kyushu Electric Power Company Buzen Substation	Toshiba	1984	UHV technology applied to a 500kV transformer
20	275kV, 1000MVA, phase-shifter	Actual item	Tohoku Electric Power Company Niigata Substation	Toshiba	1984	The world’s highest capasity phase-shifter
21	New disassembled-for-transport 275kV, 300MVA transformer	Actual item	Kansai Electric Power Company Kobe Substation	Mitsubishi Electric Corporation	1984	The first transformer transported by the new disassembled-for-transport method
22	2000kV transformer for hermetic seal testing	Actual item	Showa Electric Wire & Cable Co., Ltd. Sagamihara Office	Toshiba	1987	Testing transformer capable of being corona free at the test voltage
23	187kV, 200MVA, ultra-low-noise transformer	Actual item	Hokkaido Electric Power Company Naebo Substation	Hitachi, Ltd.	1988	Attained a low noise level of 45dB using a steel sound barrier
24	Liquid-cooled, 275kV, 300MVA, gas-insulated transformer	Actual item	Kansai Electric Power Company Hirakata Substation	Mitsubishi Electric Corporation	1990	Gas-insulated transformer with a coil core cooled by liquid flow-down
25	275kV, 250MVA, liquid-cooled, gas-insulated transformer	Actual item	Chubu Electric Power Company Abe Substation	Hitachi, Ltd.	1990	Liquid immersion-cooled, gas-insulated transformer
26	275kV, 300MVA, 60dB low-noise transformer with no soundproof panel	Actual item	Tohoku Electric Power Company Ishinomaki Substation	Hitachi, Ltd.	1992	Achieved low noise specifications of 60dB using only a direct-tank-mounted

						soundproof barrier
27	1050kV, 1000MVA transformer for UHV field demonstration testing	Actual item	Tokyo Electric Power Company Shin-Haruna Substation	Hitachi, Toshiba, Mitsubishi	1993	Test transformer with actual specified values for demonstration testing
28	Forced-gas, water cooled, 275kV, 300MVA, gas-insulated transformer	Actual item	Tokyo Electric Power Company Higashi-Shinjuku Substation	Toshiba	1994	High-capacity transformer able to be cooled only by high-pressure SF_6 gas
29	Forced-gas, forced-air cooled, 161kV, 68MVA gas-insulated transformer	Actual item	Tohoku Electric Power Company Yanaizu-Nishiyama Geothermal Power Station	Toshiba	1994	Highest-voltage, highest-capacity low-pressure gas-insulated transformer
30	New disassembled-for-transport 500kV, 1000MVA transformer	Actual item	Chubu Electric Power Company Aichi Substation	Mitsubishi Electric Corporation	1994	500kV, 1000MVA transformer with an integrated three-phase structure transported by the new disassembled-for-transport method
31	Three-phase 500kV, 1450MVA transformer	Actual item	Tokyo Electric Power Company Kashiwazaki-Kariwa Nuclear Power Station	Hitachi, Ltd.	1994	Highest capacity transformer
32	22kV, 13MVA moulded transformer	Actual item	Tokyo Metropolitan Bureau of Public Cleansing Ariake Waste Incineration Plant	Fuji Electric Co., Ltd.	1994	Highest capacity moulded transformer
33	1H DC reactor for HVDC	Actual item	Kansai Electric Power Company, Electric Power Development Company Kihoku Converter Substation Shikoku Electric Power Company, Electric Power Development Company Anan Converter Substation	Toshiba, Mitsubishi	1997	DC reactor for 500kV DC transmission
34	500kV, 1500/3MVA underground substation transformer	Actual item	Tokyo Electric Power Company Shin-Toyosu Substation	Toshiba	1997	The first 500kV underground transformer
35	275kV, 450MVA, liquid-cooled, gas-insulated, underground substation transformer	Actual item	Chubu Electric Power Company Meijo Substation	Hitachi, Ltd.	1998	The highest capacity 275kV, gas-insulated underground substation transformer

■ Reference Materials 1

Appended Reference Materials 1 provides an overview of the trends in transformer technology in Japan, showing in chronological order the time of first application or implementation of new technology through the efforts of Hitachi, Toshiba, Mitsubishi, Fuji or Meidensha, as well as listing the products to which these new technologies were applied and also record-breaking products by each company. This report was written based on this data. Figs. 6.1 to 6.7 and Tables 6.1 and 6.2 are also based on this data. This table also shows electricity-related events in Japan as well as topics related to electricity, transformers and events in global or Japanese society.

Chronological History of Transformer Technology

Year	Power Situation in Japan	Development of new transformer-related technology
1831		
1837		
1856		
1878	First arc light lit in Japan	
1879		
1881		
1882		
1883		
1885		
1886	Tokyo Electric Light Company founded	
1887	Tokyo Electric Light Company No. 2 Branch starts thermal power generation for business use	
1888	Institute of Electrical Engineers of Japan (IEEJ) founded	
1889	Osaka Electric Light Company starts AC distribution	
1890		
1891	Completion of the first hydroelectric power station for business use, Keage Power Station	
1893		The first domestically-produced transformer manufactured (Miyoshi Electric Factory)
1894		Production starts on air-cooled transformers (Shibaura Engineering Works)
1895	Kyoto Electric Railway started	
1896	Tokyo Electric Light Company starts 50Hz transmission (Asakusa Thermal Power Station)	
1897		Meidensha starts transformer production
1899	Adoption of extra-high voltage 11,000V	
1900		Production starts on oil-immersed transformers
1903		
1904		
1905		Test numbers adopted
1906		
1907	55kV transmission begins (Tokyo Electric Light Company, Komahashi-Waseda)	
1908		Hitachi starts transformer production
1909	44kV transmission begins (Tonosawa-Hodogaya)	Vacuum drying adopted Shibaura Engineering Works starts technical cooperation with GE
1910		Mitsubishi starts transformer production

		Silicon steel sheets first used (pole-mount transformers)
1911	66kV transmission begins (Nagoya Electric Light Company and others)	Silicon steel sheets and transformer oil first imported and used
1912		Production starts on induction voltage regulators
1913	77kV transmission begins (Katsuragawa Electric Power Company)	Production starts transformer oil (Nippon Oil)
1914	110kV transmission begins (Inawashiro-Tabata)	Conservators first used
1915		
1916	Electric furnace steelmaking begins (Daido Steel Company)	Research published on internal potential vibration by Kujirai, Nishi, Hou
1917		Thesis published on the transformer resonance phenomenon by Nishi, Bekku
1918		Epstein testing introduced for inspecting silicon steel sheets
1919	Dammed hydroelectricity generation begins(Nohana-minami)	First use of core-type for high-capacity transformers
1920	Japan's first load dispatching centre (Tokyo Electric Light Company, Kojimachi)	

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
	Faraday discovers the electromagnetic induction phenomenon
	Masson prevents eddy currents in stacked laminated cores by mutually insulating thin steel sheet ribbons
	Varley produces a core with a closed circuit of bundled wires
	Edison invents the light bulb
	Edison starts an electricity business in New York
	Ewing discovers the hysteresis phenomenon in iron
	Gaulard and Gibbs propose AC distribution First thermal power generation begins (USA)
	Stanley discovers the idea of counter electromotive force
	Max Deri patents a transformer for shunt-type AC distribution and names it the trans-form Core-type and shell-type transformers manufactured by Ganz (transformer lighting exhibited at the Budapest Expo) Stanley completes a transformers with an annular core of wire and a laminated sheet core structure Ganz and Stanley successfully devise parallel power distribution systems
	Wenstrom produces a three-phase, core-type transformer
	First use of transformer oil for insulation 15000V transmission (Germany)

Air-cooled system standardised for transformers up to 30kVA (Shibaura)	First Sino-Japanese War
Air-cooled 1-2kV/100V 50-100 lamp capacity (Meidensha)	
	Hadfield invents silicon steel
50kV, 4kVA test transformer developed (Shibaura)	Silicon steel industrialised in the United Kingdom
	Russo-Japanese War
First extra-high voltage 11kV, 150kVA transformer completed (for Kofu Electric) (Shibaura)	
22kV, 250kVA transformer completed (Shibaura)	
44kV, 500kVA transformer completed (Hakone Hydroelectric) (Shibaura)	
Shell-type, water-cooled, 44kV, 1500kVA transformer completed (Yokohama Electric Power Company Hodogaya Substation) (Shibaura)	
	First use of conservators
Single-phase, water-cooled 1500kVA transformer (Nagoya Electric Light Company) (Hitachi)	
66kV, 2500kVA transformer (Kyushu Hydroelectric) (Shibaura)	154kV transmission begins (USA)
	First World War
500kV test transformer (University of Tokyo) (Shibaura) Single-phase, oil-immersed, water-cooled 38kV, 2600kVA transformer (Japan Nitrogenous Fertilizer) (Hitachi)	Wagner publishes the basic concept of internal potential vibration in transformer windings
Oil-immersed, water-cooled 60kV, 2000kVA transformer (Kumamoto Electric Power Company) (Hitachi)	
110kV, 4400kVA transformer (Inawashiro Hydroelectric, Tokyo Electric Light Company Tabata Substation) (Shibaura) 350kV test transformer (Ministry of Communications) (Hitachi)	
66kV, 6000kVA transformer completed (Shibaura)	200kV transmission begins (California, USA) Production of 220kV-graded insulation transformers (USA)

Year	Power Situation in Japan	New Transformer-Related Technology Developed
1921		
1922		Domestic production of silicon steel sheets Electrical equipment standard JEC-9 established
1923	154kV transmission begins (Keihin Electric Power Company Koshin	Mitsubishi starts technical cooperation with WH

	network)	
1924		Three-winding transformer produced (Tokyo Electric Light Company, 10MVA) (Hitachi)
1925		Fuji starts transformer production through technical cooperation with Siemens
1926		77kV, 10MVA transformer transported assembled by sea (Daido Electric Power Company Shin-Yodogawa Power Station) (Shibaura) First condenser bushing produced Japan's first transformer standard JES31 issued
1927		
1928		First use of lightning-protected winding structures First use of domestically-produced silicon steel sheets Flanged collar insulation used
1929		
1930		Radiator valve invented Multi-dial thermometer used
1931		
1932		
1933		Potential distribution measured First use of surge-proof windings (Single-phase, 165kV, 7.5MVA transformer for the Taiwan Electric Taipei Substation)
1934	Pumped-storage power generation begins	Transformer standard JEC-36 established Impulse voltage generator built
1935		First use of nitrogen immersed transportation (154kV, 15MVA transformer for the Chosen Power Transmission Pyongyang Substation) Resistor-type on-load tap changers introduced (Jansen-style)
1936		Concave railcar Shiki 60 produced
1937		First impulse testing implemented (154kV, 18MVA transformer for the Ministry of Railways Musashi-Sakai Substation)
1938		Wartime standard JEC-36 Z issued
1939	6kV distribution begins (Tokyo Electric Light Company)	Assembled transportation by special freight car Shiki 60 (39MVA transformer for the Tokyo Electric Light Company Shinanogawa Power Station) First use of partially shielded windings (154kV transformer for the Tokyo Electric Light Company Shinanogawa Power Station) Invention of impulsewave waveform viewing device
1940		Impulse testing implemented on a 230kV transformer (Manchuria Electric) Non-flammable synthetic oil (PCB) immersed transformer produced (44kV, 4.5MVA transformer for Manchuria) First use of multiple cylindrical windings (220kV arc-extinguishing reactor for the Chosen Hydroelectric Heochun River Power Station) First use of a banked radiator (230kV, 80MVA transformer for the Chosen Hydroelectric Chongjin Substation)

1941		First use of a finned unit cooler(100MVA transformer for Chosen Hydroelectric) Japanese standard on mineral transformer oil issued
1942		First use of a nitrogen-filled conservator Neutral point graded insulation method developed Studies on potential vibration in 220kV transformers
1943		
1944		Load voltage regulator adjusted on the high-voltage side produced
1945		The first standard on static induction electric apparatus impulse testing JEC-110 established Studies on anisotropic silicon steel sheet core structures

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
Three-phase, 66kV, 8,000kVA transformer completed (Shibaura) Single-phase, 55kV, 5000kVA transformer (Daido Electric Power Company) (Mitsubishi)	
	Non-resonant transformer produced (USA)
2kV, 240kVA transformer for a rotary converter (Tokyo Electric Light Company) (Meidensha)	Great Kanto Earthquake Inertia transformer produced (US company WH)
Single-phase, water-cooled 77kV, 13333kVA transformer (Nippon Electric Ozone Substation) (Shibaura)	Parallel circuit on-load voltage regulating transformer (US company GE)
80kV, 15MVA transformer (Toho Electric Power Company) (Shibaura) Single-phase, 66kV, 1000kVA transformer (Teikoku Electric Light Company) (Meidensha)	Radio broadcasting begins
The first 154kV transformer (154kV, 6667kVA transformer for the Nippon Electric Gifu Substation) (Shibaura) The first forced-oil, forced-air cooled 80kV, 12.5MVA transformer (Kansai Power Distribution) (Hitachi) Water-cooled 53kV, 10MVA transformer (Kyoto Electric Light Company) (Fuji)	
Self-cooled, 10MVA transformer (Ujigawa Electric Power Company) (Shibaura) 820kVA transformer with mercury-arc rectifier (Nippon Mining Company) (Hitachi) 77kV, 22.53MVA (Tokyo Electric Light Company) (Mitsubishi)	Jansen-type cross current suppression system announced
Self-cooled, single-phase, 140kV-87kV-11kV, 22MVA transformer (Showa Electric Power Company Yao Substation) (Shibaura) 165kV, 12.5MVA transformer (Showa Electric Power Company) (Hitachi) Three-phase, water-cooled, 115kV, 36MVA transformer (Chosen Nitrogen Corporation Pujon River No. 1 Power Station) (Shibaura) Single-phase, 70kV, 7.5MVA transformer transported immersed in oil (Toho Electric Power Company Najima Substation) (Mitsubishi)	

The first 154kV, 18.833MVA transformer to be disassembled for transport (Toshin Electric Power Company Toyomi Power Station) (Hitachi) 700kV testing transformer (Osaka Togyo) (Hitachi) Forced-oil, water cooled, 60kV, 4.5MVA, 34.5kA secondary current for an electric furnace-transformer (Denki Kagaku) (Fuji)	Forced-oil, water cooled, three-phase, 100MVA transformer (Germany company AEG) The Great Depression
Three-phase, forced-oil, water cooled 72kV, 43.75MVA transformer (Nippon Electric Tsurumi Power Station) (Shibaura) The first on-load voltage regulating transformer (450kVA transformer for Chugoku Godou Electric) (Shibaura) 400kV test transformer (Fuji)	Recommendations announced on insulation coordination (USA) The first impulse testing (US company GE)
On-load voltage regulating, single-phase 110kV, 12MVA transformer (Kumamoto Electric Power Company) (Shibaura) Three-phase, water-cooled, 105kV, 23MVA transformer (Chosen Hydroelectric) (Fuji)	Water-cooled, three-phase, 60MVA transformer produced (USA)
77kV, 22MVA transformer transported immersed in oil (Toho Electric Power Company Kizu Substation, Iwakura Substation) (Shibaura) Single-phase, 147kV, 20MVA transformer (Tokyo Electric Light Company Kawasaki Substation) (Mitsubishi) On-load voltage regulating, 6300kVA transformer (Kyoto Electric Light Company) (Hitachi)	Surge-proof windings produced (US company WH)
The first 88.5MVA phase sifter (Kansai Joint Power Company Amagasaki Thermal Power Station) On-load voltage regulating, 2100kVA transformer (Sanyo Chuo Hydroelectric) (Hitachi) 39MVA,178.5kV, disassembled-for-transport transformer (Toshin Electric Power Company Shimagawara Power Station) (Hitachi)	V-t characteristics published (US company GE, WH)
Single-phase, 165kV, 15MVA transformer transported by low-floor railcar immersed in oil (Taiwan Electric) (Mitsubishi) On-load voltage regulating, three-phase, 77kV, 15MVA self-cooled transformer (Electric Power Development Company) (Hitachi)	Grain-oriented silicon steel sheets invented (US company Goss)
Three-phase, forced-oil, water cooled, 66kV, 63MVA transformer (Tokyo Electric Light Company Tsurumi No. 1 Thermal Power Station) (Shibaura) Self-cooled, three-phase, 161kV, 34.65MVA transformer (Oigawa Electric Company) (Mitsubishi) Single-phase, 66kV, 1500kVA transformer (Minami Chosen Electric Power Company) (Meidensha) Three-phase, 11kV, 3MVA, on-load tap changing transformer for an electric furnace (Japan Nitrogenous Fertilizer) (Fuji)	
Water-cooled, 154kV, 60MVA transformer (Chongjin River Hydroelectric Hagi River Substation) (Shibaura) Self-cooled, 154kV, 50MVA transformer (Chosen Power Transmission Gyeongseong Substation)	Multiple cylindrical windings (non-resonant transformer) produced (German company AEG) Impulse testing regulations issued (USA)

(Shibaura) Single-phase, 84kV, 31.25MVA transformer (Kansai Joint Power Company Amagasaki No. 2 Power Station) (Hitachi)	
Forced-oil, forced-air cooled, 154kV, 50MVA transformer (Tokyo Electric Light Company Wadabori Substation) (Shibaura) Self-cooled, 70kV, 63MVA transformer (Chubu Joint Power Company Meiko Power Station) (Shibaura)	Forced-oil, forced-air cooled, three-phase 220kV, 100MVA transformer transported by railcar (German company AEG)
The first 220kV transformer (220kV, 80MVA transformer for Chongjin River Hydroelectric Heochun River No. 1 Power Station) (Shibaura) 500kV testing transformer (Furukawa Electric Company) (Fuji)	Second World War begins
Three-phase, forced-oil, water-cooled, 230kV, 100MVA transformer (Yalu River Hydroelectric Sup’ung Power Station) (Toshiba) Single-phase, self-cooled, 230kV, 37.5MVA transformer (Manchuria Electric Andong Substation) (Hitachi) Single-phase, 220kV, 50MVA transformer (Manchuria Electric) (Mitsubishi) On-load voltage regulating, three-phase, 44/44 ±3.3kV, 150MVA transformer (Mitsubishi) Three-phase, self-cooled, 161kV, 35MVA transformer (Nippon Light Metal Niigata) (Hitachi)	
Three-phase, forced-oil, forced-air cooled, 230kV, 100MVA transformer (Chosen Hydroelectric Tasado Substation, etc.) (Toshiba) Forced-air cooled, 161kV, 70MVA transformer (Hydroelectric Construction Bureau of Manchuria Songhua River Power Station) (Hitachi) On-load tap changing, single-phase, 40kV, 5MVA transformer (Yamaguchi Prefectural Electricity Bureau) (Meidensha)	Japan-US war
Forced-air cooled, three-phase, 240kV, 30MVA transformer (Kanggye Hydroelectric) (Fuji) Three-phase, 60kV, 28MVA, 58.4kA second current, on-load tap changing transformer for an electric furnace (Japan Nitrogenous Fertilizer) (Fuji)	
Forced-air cooled, 230kV, 70MVA transformer (Hydroelectric Construction Bureau of Manchuria Songhua River Power Station) (Hitachi)	Main-gap-filling insulation structure (Swiss company BBC)
Three-phase, forced-oil, forced-air cooled, triple winding, 154/77/21kV, 33MVA transformer (Japan Electric Generation and Transmission Company Ibaraki Substation) (Hitachi)	

Year	Power Situation in Japan	New Transformer-Related Technology Developed
1948		First use of unitcooler (78MVA transformer for Showa Denko) The first neutral-point graded- insulation transformer (single-phase, 140kV, 25MVA transformer for the Electric Power Development Company Okayama Substation)
1949		

1950		Non-resonant windings (lightning-protected layered cylindrical windings) developed
1951	9 power companies established	275kV transformer produced High series capacitance windings developed First use of form-fit (single-phase, 66kV, 15MVA transformer for the Tokyo Electric Power Company Shikahama Substation) First use of main-gain-filling insulation structures First use of induction heating drying method First use of electrostatic shielding (three-phase, 154kV, 33MVA transformer for the Tohoku Electric Power Company Higashi-Niigata Substation) First use of non-resonant windings in transformers (multiple cylindrical windings) (154kV, 27MVA transformer for Tokyo Electric Power Company)
1952	275kV transmission begins (Kansai Electric Power Company Shin-Hokuriku Trunk Line) Electric Power Development Company established	Static induction electric apparatus standard JEC-120 established Post-war overseas technical cooperation resumes Shiki 120 low-floor railcar produced Use of onsite core-erecting equipment First use of magnetic tank shielding (shell-type) Test methods established for the stability of transformer oil
1953	Air circuit breakers implemented	Shiki 130 well hole railcar produced
1954		First use of damper-shield windings (120kV, 45MVA transformer for the Kyushu Electric Power Company Ainoura Power Station) First use of transposed cables Use of multi-conductor cables
1955		First use of special three-phase transformers First use of grain-oriented silicon steel sheets First use of three-phase, five-limb cores Schnabel-car-type Shiki 170 produced Automatic electric field replication technology Dial-type temperature relays, indirect resistor temperature detectors and pressure release valves adopted Development of gas-in-oil analysis method Technical cooperation begins with German company AEG (Meidensha)
1956		First use of vapor-phase drying method First use of forced winding cooling First use of floating cranes Equipment for viewing AC magnetic properties First use of high series capacitance windings First use of frame-shaped core (6MVa transformer for the Tokyo Electric Power Company Kichijoji Substation)
1957	Tokai-Mura No. 1 Nuclear Reactor ignited	Cooling-tower-type water-cooled transformer developed Shiki 400 Schnabel car produced Winding machines fitted with transposed cables
1958		Transformer short-circuit testing (70kV, 2000kVA) Shiki 300 Schnabel car produced Multi-conductor cables used Establishment of erecting equipment for large-scale cores First use of transformers with cable connections

		(elephant type) Fully equipped 10MVA transformer produced Moveable transformer produced
1959	Extremely-high-voltage cross-channel transmission line built (Kanmon, 220kV)	Core sheet cutting process line built on 400kV, 10MVA transformer prototype tested Shiki 600 Schnabel car produced

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
Three-phase, forced-oil, forced-air cooled, 154kV, 78MVA transformer (Showa Denko) (Mitsubishi) 147kV, 60MVA transformer with 6MVA on-load voltage regulator (Showa Denko Shiraishi Substation) (Hitachi)	Transistor invented (Bell Research Laboratories, USA)
Three-phase, 115kV, 15MVA on-load tap changing transformer for export (India) (Fuji)	
84kV, 20MVA transformer with a nitrogen-filled conservator (Japan Electric Generation and Transmission Company) (Hitachi)	High series capacitance windings published (EE, UK) Korean War
The first three-phase, 250kV, 99MVA transformer for 275kV (Kansai Electric Power Company Hirakata Substation) (Mitsubishi) The first three-phase, 275kV, 70MVA transformer for 275kV (Kansai Electric Power Company Narude Power Station) (Hitachi) Self-cooled, three-phase 69kV, 45MVA transformer (Kyushu Electric Power Company Chikujo Power Station) (Mitsubishi) Assembled, transported on its side by special Shiki 100 well hole railcar (45MVA transformer for Kyushu Electric Power Company Chikujo Power Station) (Mitsubishi) Non-resonant, 154kV, 27MVA transformer (Tokyo Electric Power Company Hakojima Substation) (Fuji) Three-phase, 154kV, 66MVA transformer with cooling unit (Tokyo Electric Power Company Wadabori Substation) (Toshiba) Forced-air cooled, 66kV, 37.25MVA transformer (Japan Electric Generation and Transmission Company Tsurumi Power Station) (Meidensha)	The first successful nuclear power generation (USA) single-phase 250/3MVA (WH), three-phase 138kV, 145MVA (WH) Treaty of Peace With Japan
Tripled rated, three-phase, 69kV, 33.75MVA transformer (Hokkaido Electric Power Company Sunagawa Substation) (Mitsubishi) Three-phase, 166kV/275/11kV, 99MVA transformer (Kansai Electric Power Company Shin-Aimoto Substation) (Toshiba) The first 77kV, 15MVA reactor (Kansai Electric Power Company Hirakata Substation) (Toshiba) The first low-noise, three-phase, forced-oil, self-cooled, 63kV, 15MVA transformer (Tokyo Electric Power Company Hibiya Substation) (Hitachi) Assembled, transported on its side by special Shiki 120 railcar (65MVA transformer for Kyushu Electric Power Company Chikujo Power Station) (Mitsubishi)	400kV transmission begins (Sweden)

Forced-oil, water-cooled, three-phase, 66kV, 42MVA, 10kA second current transformer for an electric furnace (New Japan Nitrogenous Fertilizer Company) (Fuji) Form-fit, assembled ,transported on its side, three-phase, 147kV, 39MVA transformer (Tokyo Electric Power Company Higashi-Chiba Substation) (Mitsubishi)	
Non-resonant, three-phase, 275kV, 45MVA transformer (Kansai Electric Power Company Tsubakihara Power Station) (Fuji) Assembled-for-transport, 154kV, 50MVA transformer (Tokyo Electric Power Company Kawasaki Substation) (Toshiba) Double rating of high-voltage, single-phase, 250-154kV 72.5MVA transformer (Kansai Electric Power Company Maruyama Power Station) (Mitsubishi) Fahrbar-type, three-phase, 110kV, 50MVA transformer (Kyushu Electric Power Company Chikujo) (Fuji)	
Three-phase, forced-oil, forced-air cooled, 230kV, 135MVA transformer (Kyushu Electric Power Company Kamishiiba Power Station) (Hitachi) Assembled-for-transport, 154kV, 66MVA transformer (Tokyo Electric Power Company Musashino Substation) (Toshiba) 154kV, 66MVA transformer transported assembled by Shiki 140 Schnabel car (Tokyo Electric Power Company Keihoku Substation) (Hitachi)	Vapor-phase drying method (GE, USA)
Assembled-for-transport, 154kV, 99MVA transformer (Chubu Electric Power Company Higashi-Nagoya Substation) (Toshiba) Special three-phase, 275kV, 93MVA transformer (Electric Power Development Company Sakuma Power Station) (Mitsubishi) Low-noise, three-phase, 66kV, 30MVA transformer (Tokyo Electric Power Company Sumida Substation) (Mitsubishi) 55dB low-noise, three-phase, 66kV, 30MVA transformer (Tokyo Electric Power Company Inari Substation) (Meidensha) 154kV, 65MVA ,three-phase, five-leg core transformer (JPA-Korea) (Meidensha) 275kV, 132MVA transformer (Electric Power Development Company Nishi-Tokyo) (Hitachi) Fully equipped sealed 2MVA transformer (Tohoku Electric Power Company Kitakata Substation) (Hitachi)	
Low-noise 154kV, 110MVA transformer (Tokyo Electric Power Company Toda Substation) (Toshiba) The first three-phase, forced-oil, forced-air cooled, 154kV, 160MVA transformer with forced winding cooling (Tokyo Electric Power Company Chiba Power Station) (Toshiba) On-load voltage and phase regulating, 220kV	Start of commercial nuclear reactor operation (Calder Hall Nuclear Power Station, UK) Japan joined the UN Thyristors released on the market (GE, USA)

±10,±j30kV, 90MVA transformer (Kyushu Electric Power Company Yamaie Substation) (Toshiba) 48dB low-noise, 66kV, 30MVA transformer (Tokyo Electric Power Company Itabashi Substation) (Hitachi) Assembled-for-transport, 66MVA transformer with a five-limb core (Kansai Electric Power Company Furukawabashi Substation) (Hitachi) On-load tap changing, 110kV, 60MVA transformer (Kyushu Electric Power Company Shinohara Power Station) (Meidensha) Dry-type, H-grade-insulated, 3000kVA transformer with tap changer (Kansai Electric Power Company Dojima Substation) (Hitachi) 99MVA transformer transported assembled by Shiki 140 railcar (Chubu Electric Power Company Iwakura Substation) (Hitachi) 78MVA transformer transported assembled by Shiki 120 Schnabel car (Tokyo Electric Power Company Suruga Substation) (Mitsubishi)	
Cooling-tower-type water-cooled, 66kV, 30MVA transformer (Tokyo Electric Power Company Otemachi Substation) (Mitsubishi) On-load tap changing, 110kV, 66MVA transformer (Chugoku Electric Power Company Tokuyama Substation) (Toshiba) 27.5MVA reactor (Kansai Electric Power Company Shin-Aimoto Substation) (Toshiba) On-load tap changing, 110kV, 70MVA transformer (Kyushu Electric Power Company Omura Power Station) (Hitachi) Low-noise, 45MVA transformer with sound barrier structure (Tokyo Electric Power Company Takanawa Substation) (Hitachi) On-load tap changing, 154kV, 30MVA transformer (Kansai Electric Power Company Shin-Yawata Substation) (Fuji)	
Special three-phase, 275kV, 260MVA transformer with frame-shaped core (Tokyo Electric Power Company Naka-Tokyo Substation) (Mitsubishi) Three-phase, 275kV, 200MVA transformer (Tokyo Electric Power Company Chiba Power Station) (Toshiba) On-load tap changing, 120MVA transformer transported assembled by Schnabel car (Tohoku Electric Power Company Honmyo Substation) (Mitsubishi) 220kV, 180MVA transformer transported assembled by Schnabel car (Kyushu Electric Power Company Nishitani Substation) (Hitachi) 2500kVA transformer with Scott connection (Japanese National Railways Tohoku Main Line Kuroiso Substation) (Hitachi) The first (elephant) cable connected, three-phase, 66kV, 6MVA transformer (Furukawa Chemical) (Fuji)	500kV transmission begins (USSR)

Moveable 70kV, 3MVA transformer (Chubu Electric Power Company) (Meidensha) Fully equipped, 66kV, 10MVA transformer (Tokyo Electric Power Company Shibue Substation) (Meidensha)	
Three-phase, 275kV, 270MVA transformer (Chubu Electric Power Company Shin-Nagoya Power Station) (Toshiba) Special three-phase, 275kV, 264MVA transformer (Electric Power Development Company Minami-Kawagoe Substation) (Mitsubishi) 70kV, 20MVA shunt reactor (Kansai Electric Power Company Shikitsu Substation) (Hitachi) Assembled-for-transport, three-phase, 275kV, 264MVA transformer (Electric Power Development Company Nishi-Tokyo Substation) (Hitachi) Three-phase 154kV, 75MVA transformer with embedded on-load tap changer (Tokyo Electric Power Company Kuramae Substation) (Fuji) Assembled-for-transport, three-phase, 275kV, 200MVA transformer (Kansai Electric Power Company Higashi-Osaka Substation) (Fuji)	

Year	Power Situation in Japan	New Transformer-Related Technology Developed
1959		
1960	154kV underground substation (Tokyo Electric Power Company Chiyoda Substation) 275kVOF cable	First use of diaphragm-type conservators First use of hot line oil purifiers First use of 154, 275kV cable-connected transformers First use of oil-immersed resin-bonded insulation cylinders First use of crêpe insulation paper First use of paper-wound soft copper twist wires and flexible copper twist wires Field mapping using resistance paper UHV testing facility completed First use of radial core shunt reactors
1961		Use of hot oil spray drying method First use of concrete sound barriers
1962		First use of hourglass insulation First use of thermal upgraded insulating paper
1963	Japan's first nuclear power generation begins	Technical cooperation on LTCs begins with MR First use of electromagnetic tank shielding First use of air-tight kraft insulating paper First use of tap winding float prevention resistors First use of crimping terminal for lead connection Start of overseas expansion of transformer technology (joint venture with the Kerala State Government, India)
1964		First production of dry-type condenser bushings First use of double-piped cooler (Tokyo Electric Power Company Babasaki Substation) First use of aluminium coils
1965	Uniform specifications for on-load tap changing transformers 500kV transmission line constructed	Operating survey conducted and accident statistics compiled for on-load tap changing transformers (Electric Technology Research Association)

	(Tokyo Electric Power Company Boso Line) First frequency converter station grid connection (Electric Power Development Company Sakuma)	Introduction of partial discharge testing Gas-in-oil analysis developed Adoption of bound cores Coil assembly rooms fitted with air conditioning facilities Development of two-dimensional magnetic field calculation technology
1966		CC shield windings developed and implemented Introduction of large-scale vertical winding machines First painting of internal structure materials Winding short circuit vibration analysis programme developed Transformer standard JEC-168 established Adoption of E-type insulation method Introduction of switching impulse testing Double concentric winding structures applied to high-capacity transformers Adoption of slit core backing plates Adoption of clamped magnetic shields
1967		Gas-in-oil analysis introduced to test evaluation Introduction of high vacuum exhaust systems Introduction of insulation moisture control Acoustic corona location technology established Introduction of corona-free adhesive Introduction of low-humidity, dust-proof, air conditioned rooms First hot oil circulation Pressboard changes from second hand cotton type to new cotton type Computerisation of properties calculations Trial production of resistor-type vacuum switch LTCs Transformer technical cooperation with overseas discontinues (Toshiba)

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
400kV, 200MVA transformer for testing UHV circuit breakers (Hitachi Research Laboratory) (Hitachi)	
Assembled-for-transport, three-phase, 275kV, 260MVA transformer (Tokyo Electric Power Company Keihin Substation) (Mitsubishi) Special three-phase, 154kV, 100MVA, underground substation transformer (Tokyo Electric Power Company Chiyoda Substation) (Toshiba) Special three-phase, 275kV, 133MVA, underground power station transformer (Electric Power Development Company Okutadami Power Station) (Toshiba) Three-phase, 275kV, 300MVA transformer (Tokyo Electric Power Company Yokosuka Power Station) (Toshiba) 77kV, 50MVA cable conneted transformer (elephant coupling) (Chubu Electric Power Company Nanbu-Tairamachi Substation) (Meidensha) 77kV, 20MVA transformer with shunt reactor	

(Kansai Electric Power Company Hirakata Substation) (Meidensha) Three-phase, 275kV, 150MVA, cable connected transformer (elephant coupling) (Tokyo Electric Power Company Yokosuka Power Station) (Fuji)	
330kV, 100MVA, on-load tap changing, auto-transformer (Sydney Substation, Australia) (Toshiba) 330kV, 160MVA, on-load tap changing, auto-transformer (Vales Point Power Station, Australia) (Hitachi) Low-noise three-phase, 90MVA transformer with concrete sound barrier (Chubu Electric Power Company Mizuho Substation) (Fuji) 275/220kV, 200MVA auto-transformer for grid interconnection (Kansai Electric Power Company Himeji Substation) (Fuji) 1500kVA, PCB-insulating-oil-immersed transformer (Tokyo Electric Power Company Kawasaki Thermal Power Station) (Hitachi) 77kV, 180MVA , cable connected transformer (elephant coupling) transformer (Kansai Electric Power Company Himeji Power Station) (Mitsubishi) 154kV, 100MVA transformer with diaphragm conservator (Kansai Electric Power Company Yokooji Substation) (Meidensha)	
220kV, 111.5MVA auto-transformer for grid interconnection (Electric Power Development Company Iyo Substation) (Mitsubishi) Assembled-for-transport, 275kV, 300MVA transformer (Tokyo Electric Power Company Kita-Tokyo Substation) (Mitsubishi) Assembled-for-transport, on-load tap changing, three-phase, 63kV, 45MVA transformer for an electric furnace (Denki Kagaku) (Fuji) Disassembled-for-transport, 200MVA transformer (Chubu Electric Power Company Kawane Substation) (Hitachi) On-load tap changing, 220kV, 150MVA transformer with hot line oil purifier (Chugoku Electric Power Company Yamaguchi Substation) (Meidensha)	
Three-phase, 275kV, 370MVA transformer (Kansai Electric Power Company Himeji No. 2 Power Station) (Mitsubishi) High impedance, three-phase, 275kV, 420MVA transformer (Tokyo Electric Power Company Yokosuka Power Station) (Toshiba) Three-phase, 275kV, 430MVA transformer (Chubu Electric Power Company Owasemita Thermal Power Station) (Toshiba) Assembled-for-transport, 262.5kV, 300MVA transformer (Chubu Electric Power Company Nishi-Nagoya Substation) (Hitachi) Transformer with built-in LTC (Tohoku Electric Power Company Shin-Sanjo Substation) (Toshiba) 14.7kV, 40MVA reactor (Electric Power Development Company Minami-Kawagoe Substation) (Mitsubishi)	

30MVA transformer with Scott connection (Tokaido Shinkansen line) (Mitsubishi, Toshiba)	
275kV, 368, 353MVA frequency converter transformer (Electric Power Development Company Sakuma Frequency Converter Station) (Mitsubishi) Transformer with built-in rotary resistive LTC (Kansai Electric Power Company Shin-Kakogawa Substation) (Hitachi) Special three-phase, 275kV, 300MVA transformer (Tokyo Electric Power Company Kita-Tokyo Substation) (Mitsubishi) Assembled-for-transport, 275kV, 300MVA transformer (Electric Power Development Company Nagoya Substation) (Fuji) Assembled-for-transport, 275kV, 200MVA transformer (Tokyo Electric Power Company Shin-Fuji Substation) (Meidensha) Low-noise, 140kV, 25MVA transformer with concrete sound barrier (Tokyo Metropolitan Government Bureau of Waterworks Asaka Purification Plant) (Hitachi) DC66kA rectifier transformer rectifying element with embedded in tank (Kanto Denka) (Fuji)	Tokaido Shinkansen opens Tokyo Olympics
Special three-phase, 345kV, 400MVA transformer (Munmorah Power Station, Australia) (Mitsubishi) 275kV, 300MVA transformer transported with built-in LTC (Tokyo Electric Power Company Higashi-Tokyo Substation) (Hitachi)	New York blackout 735kV transmission begins (Canada)
Three-phase, 275kV, 680MVA transformer (Tokyo Electric Power Company Anegasaki Power Station) (Toshiba) 275kV, 300MVA transformer transported with built-in LTC (Tokyo Electric Power Company Koto Substation) (Toshiba) Transformer for 500kV voltage impression testing (Takeyama Ultra High Voltage Laboratory) (Hitachi, Toshiba, Mitsubishi) 400kV transformers (around 50 3000MVA transformers for Mexico) (Mitsubishi)	
500kV transformers for export (80, 100, 200MVA transformers for BCHPA, Canada) (Toshiba) Three-phase, 66kV, 3000kVA, gas-insulated transformer (Daiichi Life) (Toshiba) Three-phase, 275kV, 510MVA transformer with LVR (Kansai Electric Power Company Himeji No. 2 Power Station) (Mitsubishi) 236kV, 125MVA reactor for export (Canada) (Mitsubishi) Three-phase, 154kV, 420MVA transformer (Tokyo Electric Power Company Goi Power Station) (Hitachi) 420kV, 35MVA reactor for export (CFE, Mexico) (Mitsubishi) Three-phase, 63kV, 50MVA, 112kA secondary current transformer for an electric furnace (Denki Kagaku) (Fuji) Three-phase, 154kV, 53MVA transformer with transposed cables (Hokuriku Electric Power	

Company Nishi-Kadohara No. 3 Power Station) (Fuji) Ultra-low-noise, 220kV, 180MVA, 45dB transformer (Kyushu Electric Power Company Nishi-Fukuoka Substation) (Meidensha) 154kV, 100MVA underground substation transformer (Tokyo Electric Power Company Togoshi Substation) (Meidensha)	

Year	Power Situation in Japan	New Transformer-Related Technology Developed
1967		First actual SF_6 insulated transformer introduced
1968	First GIS substation	Long-term insulation reliability testing implemented for 500kV transformers Silicon steel annealing discontinued
1969		Compact aluminium coolers adopted
1970	275kVGIS (Tokyo Electric Power Company Kitatama Substation)	Long-term voltage impression testing on 735kV prototype transformer Numerical analysis of potential vibration in coils Panel-type soundproof tank adopted Moulded transformer developed
1971	275kV underground substation (Tokyo Electric Power Company Shinjuku Substation)	Systematisation of volume theory Production of domestic 500kV transformers UHV development laboratory built 500ton trailer used Woodbridge-connected, 220kV, 200MVA transformer (Japanese National Railways Sanyo Shinkansen line) transformer winding short-circuit-resistant design guidelines published (IEEJ Report) Resin in-oil spacers first used Electric field analysis using filter paper method
1972		High grain-oriented silicon steel sheets first used Gas-in-oil automatic monitoring system developed Investigation begins on the flow electrification phenomenon High-density press board adopted
1973	500kV transmission begins (Tokyo Electric Power Company Boso Line)	Winding oil flow visualisation technology developed Expansion overseas (transformer factory operating in Brazil) Magnetic tank shielding first used (core type)
1974	500kVOF cable introduced	Transformer accidents due to the flow electrification phenomenon Three-dimensional magnetic field analysis technology Non-magnetic casing eddy current analysis 50dB, forced-oil, forced-air cooled cooling system developed Five-leg core adopted for ultra-high-capacity transformer Tank flange reinforcing structure adopted
1975		Heat sealed transposed cables first used Widespread use of new insulation materials such as press board structural materials, moulded insulation and reinforced wood Air pallet transportation method introduced Maintenance guidelines recommended for high-capacity transformers (Electric Technology Research Association)

		Tank and bushing reinforcement recommended as a means of preventing accidents worsening (Electric Technology Research Association) Increased use of continuous disc windings for 275kV No-bake cores first used
1976	275kV gapless arrester commercialised	Recommendations for onsite operation methods and control values for 500, 275, 154kV high-capacity transformers (Electric Technology Research Association) Flow electrification solution and prevention technology established Transformer oil charge level management implemented Potential vibration analysis technology established Overseas technology licence (Elektrimunion, Poland)
1977	Substation noise reduction status survey	Electric field analysis / magnetic field analysis technology established Automatic gas analysis equipment developed Transportation of 500kV transformers with main covers on becomes the norm Guidelines issued on transformer noise reduction measures (Electric Technology Research Association)

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
Special three-phase, 275kV, 222MVA transformer transported in six partitions (Tokyo Electric Power Company Azumi Power Station) (Mitsubishi) Single-phase, 500kV, 400MVA transformer for export (BPA, USA) (Toshiba) 65dB low-noise transformer (270MVA transformer for Kyushu Electric Power Company Oita Power Station) (Hitachi) Single-phase, 525kV, 900/3MVA transformer for export (BPA, USA) (Fuji)	High grain-oriented silicon steel sheets developed (Yawata Iron & Steel Company)
275kV, 300MVA underground substation transformer (Tokyo Electric Power Company Jonan Substation) (Toshiba) Single-phase, 400kV, 1000/3MVA transformer for export (ESKOM, South Africa) (Mitsubishi) Three-phase, 262.5kV, 490MVA transformer (Kansai Electric Power Company Kainan Power Station) (Hitachi) 132kV, 4 × 34MVA, DC213.6kADirectory step down rectifier transformer (ALCAN) (Fuji)	Apollo moon landing
Three-phase, 275kV, 680MVA transformer (Tokyo Electric Power Company Kashima Power Station) (Mitsubishi) Low-noise, 275kV, 300MVA transformer (Chubu Electric Power Company Mikawa Substation) (Hitachi) Single-phase, 525kV, 1000/3MVA auto-transformer (BPA, USA) (Hitachi) 275kV, 700MVA phase shifter (Tokyo Electric Power Company Boso Substation) (Toshiba) 66kV, 10MVA truck-transportable transformer (Tohoku Electric Power Company) (Meidensha)	Osaka World Expo

Three-phase, 275kV, 870MVA transformer (Tokyo Electric Power Company Fukushima No. 1 Nuclear Power Station) (Toshiba) Domestic single-phase, 500kV, 1000/3MVA auto-transformer (Tokyo Electric Power Company Shin-Koga Substation) (Toshiba) Domestic single-phase, 500kV, 1000/3MVA auto-transformer (Tokyo Electric Power Company Boso Substation) (Mitsubishi) 275kV, 200MVA underground substation transformer (Tokyo Electric Power Company Shinjuku Substation) (Mitsubishi) Special three-phase, 275kV, 335MVA transformer with six partitions (Tokyo Electric Power Company Tamahara Power Station) (Mitsubishi) Three-phase, 262.5kV, 660MVA transformer (Kansai Electric Power Company Kainan Power Station) (Hitachi) 60MVA transformer for a high-capacity arc furnace (Yahagi Steel) (Toshiba)	
66kV, 80MVA reactor (Tokyo Electric Power Company Jonan Substation) (Toshiba)	
Three-phase, 275kV, 1100MVA transformer (Tokyo Electric Power Company Kashima Power Station) (Toshiba) On-load tap changing, 275kV, 660MVA transformer (Kansai Electric Power Company Himeji No. 2 Power Station) (Toshiba) Single-phase, 500kV, 1000/3MVA auto-transformer (Tokyo Electric Power Company Shin-Fukushima Substation) (Hitachi) Three-phase, 500kV, 640MVA transformer (Kansai Electric Power Company Okutataragi Pumped Storage Power Station) (Hitachi) 275kV, 860MVA transformer with on-load voltage regulator (Kansai Electric Power Company Takahama Power Station) (Mitsubishi) On-load tap changing, 275kV, 450MVA transformer (Tokyo Electric Power Company Kohoku Substation) (Mitsubishi) Single-phase, separate-winding, 500kV, 250MVA transformer (Kansai Electric Power Company Inagawa Substation) (Toshiba) On-load voltage phase regulating, 268.8kV, 250MVA transformer (Tohoku Electric Power Company Niigata Substation) (Meidensha) 154kV, 80MVA reactor (Tokyo Electric Power Company Ooi Thermal Power Station) (Meidensha)	1973 oil crisis
Special three-phase, 500kV, 640MVA transformer (Kansai Electric Power Company Okutataragi Pumped Storage Power Station) (Mitsubishi) Assembled-for-transport, 275kV, 450MVA LRT transformer (Chubu Electric Power Company Sunen Substation) (Toshiba) Three-phase, 500kV, 1100MVA transformer (Tokyo Electric Power Company Sodegaura Power Station) (Toshiba) Special three-phase, 345kV, 500MVA transformer	

(Taiwan Electric) (Fuji) Moulded transformers go on sale (Fuji) 66kV, 15MVA transformer for GIS substation (Tokyo Electric Power Company Fujine Substation) (Meidensha) Single-phase, separate-winding, 500kV, 250MVA transformer (Kansai Electric Power Company Shin-Ikoma Substation) (Hitachi) 60kV, 13.5MVA, Shinkansen booster- transformer (Japanese National Railways Tokuyama Substation) (Meidensha)	
275kV, 150MVA reactor (Tokyo Electric Power Company Kitatama Substation) (Toshiba) Three-phase, 500kV, 1100MVA transformer (Tokyo Electric Power Company Sodegaura Power Station) (Mitsubishi) Three-phase, 275kV, 1200MVA transformer (Japan Atomic Power Company Tokai No. 2 Nuclear Power Station) (Mitsubishi) 400kV, 50MVA reactor (Iran) (Mitsubishi)	
Single-phase, 500kV, 500MVA auto-transformer (Tokyo Electric Power Company Boso Substation) (Mitsubishi) Three-phase, 500kV, 1240MVA transformer (Kansai Electric Power Company Oi Nuclear Power Station) (Mitsubishi) 275kV, 150MVA reactor (Tokyo Electric Power Company Keihoku Substation) (Mitsubishi) Three-phase, 275kV, 680MVA transformer (Tokyo Electric Power Company Anegasaki Power Station) (Hitachi)	
Single-phase, separate-winding, 500kV, 250MVA transformer (Kansai Electric Power Company Shigi Substation) (Mitsubishi) Moulded transformer production starts (Mitsubishi) 500kV, 50MVA reactor (Brazil) (Mitsubishi) Three-phase, 500kV, 1200MVA transformer (Tokyo Electric Power Company Fukushima No. 1 Nuclear Power Station) (Toshiba) Single-phase, 500kV, 500MVA auto-transformer (Tokyo Electric Power Company Shin-Koga Substation) (Toshiba) 500kV, 680MVA transformer transported in nine partitions (Kansai Electric Power Company Okuyoshino Pumped Storage Power Station) (Toshiba) 125kV, 187MVA DC conversion transformer (Tokyo Electric Power Company Shin-Shinano Frequency Converter Substation) (Toshiba, Hitachi) 275kV, 450MVA LRT transformer transported assembled with built-in LTC (Chubu Electric Power Company Kitatoyoda Substation) (Fuji)	New York blackout

Year	Power Situation in Japan	New Transformer-Related Technology Developed
1977		
1978	Status survey of earthquake damage to substation equipment	Widespread use of work-hardened copper wire UHV test transformer completed

	Substation equipment damaged by Miyagi earthquake	Earthquake-resistant transformer design method specified (Electric Technology Research Association) Transformer standard JEC-204 established Vacuum-valve LTC developed Computer-based seismic proof analysis method established Transportation for onsite installation by air bearings
1979	On-load tap changing distribution transformers standardised Hokkaido-Honshu DC grid interconnection started	Trial use of the new disassembled-for-transport system for transformers High efficiency coolers used with FRP fans
1980		Investigation into various properties of composite insulation UHV test transformer long-term reliability testing BTA-added transformer oil first used MR new-series LTCs first used GEORG's automatic core cutting machine introduced Seismic strength testing conducted on substation equipment
1981		Gas-in-oil analysis maintenance criteria established (Electric Technology Research Association) UHV technology first used on transformers of 500kV and under Highly effective direct-mounted soundproofing plates first used 147kV gas-insulated transformer prototype completed
1982		ZnO arresters used in oil to protect tap windings Magnetic-domain-refined silicon steel sheets first used Cooler variable speed control developed
1983		Seismic proof transformer bushing design established (Electric Technology Research Association) Amorphous transformer developed
1984		Step-lap stacked cores first used Press board in-oil spacers first used Low-noise, 275kV, 300MVA, 70dB transformer with no soundproof panels completed 275kV gas-insulated transformer prototype completed First use of a new disassembled-for-transport type transformer
1985		Explosion-proof transformer tank experiments conducted Internal pressure analysis method for transformer tanks presented (Electric Technology Research Association) Automated core-leg stacking equipment first used
1986		Ultra-high-capacity non-partitioned CC shielded continuous disc winding used
1987	Major black-out in the Tokyo Metropolitan area	
1988	Construction started on UHV transmission line (Tokyo Electric Power Company)	Guidelines issued on new insulation design concepts (Electric Technology Research Association)

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
Single-phase, 500kV, 750/3MVA transformer transported by rail with main cover on (Kansai Electric Power Company Minami-Kyoto Substation) (Hitachi) 72MVA transformer for high-capacity arc furnace (Tokyo Steel, Okayama) (Toshiba) 154kV, 20MVA transformer for GIS substation (Tokyo Electric Power Company Naruse Substation) (Meidensha)	
GIS direct-coupled, single-phase, 500kV, 1000/3MVA auto-transformer (Kyushu Electric Power Company Kita-Kyushu Substation) (Toshiba) GIS direct-coupled, single-phase, 500kV, 1000/3MVA auto-transformer (Kyushu Electric Power Company Chuo Substation) (Hitachi) GIS direct-coupled, single-phase, 500kV, 1000/3MVA auto- transformer (Kyushu Electric Power Company Nishi-Kyushu Substation) (Mitsubishi) 1550/√3kV transformer for UHV transmission testing (Central Research Institute of Electric Power Industry, Takeyama) (Fuji) World's highest capacity class three-phase, 13.8kV, 67MVA, DC68kA rectifier transformer (Canada) (Fuji) Three-phase, 525kV, 1100MVA transformer (Tokyo Electric Power Company Sodegaura Power Station) (Hitachi) 500kV, 50MVA with two-winding, radial core shunt reactor (Argentina, Uruguay) (Fuji) World's highest capacity moulded 22kV, 7.5MVA transformer (Japanese National Railways, Sendai Station) (Fuji) Single-phase, 512.5kV, 1200/3MVA transformer (Canada) (Fuji) Assembled-for-transport, 275kV, 450MVA transformer (Chubu Electric Power Company Sunen Substation) (Meidensha) Forced-gas, forced-air cooled, 66kV, 10MVA transformer (Joetsu Shinkansen) (Meidensha) 275kV, 300MVA underground substation transformer (Tokyo Electric Power Company Setagaya Substation) (Meidensha) 275kV, 150MVA underground substation reactor (Tokyo Electric Power Company Setagaya Substation) (Meidensha)	
250kV, 187MVA DC conversion transformer (Electric Power Development Company Hokkaido-Honshu grid interconnection) (Hitachi, Toshiba) Forced-gas, forced-air cooled, gas-insulated, 66kV, 10MVA transformer (Asahi Shimbun) (Toshiba) 500kV, 1000/3MVA transformer transported assembled with in-built LTC (Kansai Electric Power Company Seiban Substation) (Fuji) Special three-phase, 275kV, 300MVA underground	Three Mile Island Nuclear Accident 1979 oil crisis

substation transformer (Tokyo Electric Power Company Nerima Substation) (Fuji) Special three-phase, 275kV, 150MVA reactor (Tokyo Electric Power Company Nerima Substation) (Fuji) 80dB, three-phase, 275kV, 680MVA transformer with no sound barrier (Tohoku Electric Power Company Akita Power Station) (Hitachi)	
275kV, 200MVA reactor (Tokyo Electric Power Company Niiza Substation) (Mitsubishi) Evaporation-cooled, gas-insulated, 77kV, 40MVA transformer (Kansai Electric Power Company Hokusetsu Substation) (Mitsubishi) 500kV, 120MVA reactor (Argentina) (Fuji) 500kV, 670MVA transformer transported by rail (Tokyo Electric Power Company Shin-Haruna Substation) (Fuji) Single-phase, 500kV, 855/3MVA transformer (Argentina) (Fuji) Single-phase, on-load tap changing, 500kV, 500/3MVA auto-transformer (Tokyo Electric Power Company Shin-Okabe Substation) (Hitachi)	
2200kV testing transformer (Mitsubishi) 1400kV testing transformer (Toshiba) 1000kV gas-insulated testing transformer (Mitsubishi) Single-phase, separate-winding, 500kV, 750/3MVA transformer using UHV technology (Tokyo Electric Power Company Shin-Hadano Substation) (Toshiba) 1550/√3kV, 6MVA transformer for UHV transmission testing (Central Research Institute of Electric Power Industry, Akagi) (Fuji) 525kV, 1200/3MVA transformer (Australia) (Fuji)	
765kV, 805/3MVA transformer (Venezuela) (Hitachi, Toshiba, Mitsubishi) Three-phase, 241.5kV, 680MVA transformer (Thailand) (Fuji) Single-phase, 500kV, 1500/3MVA auto-transformer using UHV technology (Chubu Electric Power Company Shin-Mikawa Substation) (Hitachi) Three-phase, 525kV, 1200MVA transformer (Tokyo Electric Power Company Fukushima No. 2 Power Station) (Hitachi) Low-noise, 220kV, 650MVA transformer with highly efficient soundproofing plate (Kyushu Electric Power Company Shin-Kokura Power Station) (Hitachi) Gas-insulate, on-load tap changing, 66kV, 11MVA transformer (Sapporo City Transportation Bureau) (Fuji)	
275kV, 450MVA transformer with variable speed controlled cooler (Chubu Electric Power Company Seino Substation) (Meidensha) 525kV, 300MVA transformer with variable speed controlled cooler (Kansai Electric Power Company Gobo Substation) (Hitachi) Gas-insulated, 66kV, 8MVA transformer (Teito Rapid Transport Authority Mukaihara Substation)	

(Hitachi)	
275kV, 1000MVA phase sift regulator (Tohoku Electric Power Company Niigata Substation) (Toshiba) New disassembled-for-transport type, 275kV, 300MVA transformer (Kansai Electric Power Company Kobe Substation) (Mitsubishi) Evaporation-cooled, gas-insulated, 77kV, 20MVA transformer (Kansai Electric Power Company Nishi-Shirahama Substation) (Mitsubishi) 70dB, 275kV, 300MVA transformer with no sound barrier (Tohoku Electric Power Company Sukagawa Substation) (Hitachi) 126MVA transformer for an arc furnace (SICARTSA, Mexico) (Toshiba)	1150kV transmission begins (USSR)
Three-phase, 500kV, 1260MVA transformer (Japan Atomic Power Company Tsuruga Nuclear Power Station) (Toshiba) 765kV, 400/3MVA reactor (ESKOM, South Africa) (Toshiba, Fuji) Gas-insulated, on-load tap changing, 66kV, 10MVA transformer (KDD) (Toshiba) Gas-insulated, on-load tap changing, 64.5kV, 30MVA transformer (Hokkaido Electric Power Company Minami-Sanjo Substation) (Mitsubishi) Single-phase, 765kV, 2000/3MVA, auto-transformer (South Africa) (Fuji)	Tsukuba International Exposition
Three-phase, 500kV, 1200MVA transformer (Tokyo Electric Power Company Fukushima No. 2 Nuclear Power Station) (Hitachi) Self-cooled, gas-insulated, 66kV, 10MVA transformer (Yokohama City Transportation Bureau Maioka Substation) (Hitachi) 275kV, 200MVA gapped-core shunt reactor (Tokyo Electric Power Company Keihin Substation) (Mitsubishi) Gas-insulated, on-load tap changing, 66kV, 20MVA transformer (Sapporo City Transportation Bureau) (Meidensha)	Chernobyl Nuclear Disaster US makers withdrawn from US transformer businesses
2000kV corona-free testing transformer (Showa Electric Wire & Cable Company Sagamihara) (Toshiba) Self-cooled, gas-insulated, 66kV, 20MVA transformer (Sapporo City Transportation Bureau) (Mitsubishi) 3-windings, 525/147kV, 1100MVA transformer for combined cycle (Tokyo Electric Power Company Futtsu Power Station) (Hitachi) 400kV, 100MVA reactor (South Africa) (Mitsubishi)	Honshu-Shikoku cross-link complete Japanese National Railways privatised
Ultra-low-noise, 187kV, 200MVA,43dB transformer (Hokkaido Electric Power Company Naeho Substation) (Hitachi) High-impedance, 500kV, 1500/3MVA transformer (Tokyo Electric Power Company Shin-Keiyo Substation) (Hitachi)	

Year	Power Situation in Japan	New Transformer-Related Technology Developed
1988		
1989		LTCs completed for high-capacity, gas-insulated transformers First use of low-dielectric-constant press board Studies on DC bias magnetism from magnetic storms
1990		
1991		
1992		
1993		
1994		
1995		Transformer standard JEC-2200 established
1996		
1997	500kV underground substation (Tokyo Electric Power Company Shin-Toyosu Substation)	High-capacity transformer factory operating in China
1998		500kV, 250MVA short-circuit test implemented
1999		Transformer deterioration diagnosis guidelines issued (Electric Technology Research Association) Review of guidelines for gas-in-oil analysis diagnosis methods (Electric Technology Research Association) Maintenance management method proposed for flow electrification (Electric Technology Research Association)
2000		Ultra-compact, new shell-type transformer completed
2001		
2002		
2003		

Main Transformer Products	Social Situations, Electricity/Transformer Situation Overseas, Other
Single-phase, 765/500kV, 1650/3MVA auto-transformer (FURNAS, Brazil) (Toshiba) 275kV, 200MVA reactor (Chubu Electric Power Company Umemori Substation) (Toshiba) 275kV, 300MVA transformer together with phase shifter (Tohoku Electric Power Company Akita Substation) (Mitsubishi)	
Liquid-cooled, gas-insulated, 154kV, 200MVA transformer (Tokyo Electric Power Company Asahi Substation) (Toshiba) Self-cooled, gas-insulated, 66kV, 30MVA transformer (Kyushu Electric Power Company Yatsushiro Substation) (Toshiba) New disassembled-for-transport type, 220kV, 250MVA transformer (Kyushu Electric Power Company Kamishiiba Power Station) (Hitachi) 275kV, 250MVA+20MVAR transformer with in-built shunt reactor (Chubu Electric Power Company Toshin Substation) (Mitsubishi) 275kV, 250MVA reactor (Kuwait) (Mitsubishi) Single-phase, 765/345kV, 1500/3MVA auto-transformer (FURNAS, Brazil) (Hitachi) 18.5MVA cycloconverter power supply transformer for variable speed pumped storage (Tokyo Electric Power Company Yagisawa Power Station) (Toshiba)	

Gas-insulated, three-phase, 64.5kV, 30MVA transformer for waste heat recovery (Tohoku Electric Power Company Honmachidori Substation) (Fuji) 40kA secondary current, 15MVA transformer for a DC arc furnace (Daido Steel Company, Hoshizaki) (Toshiba)	
Liquid-cooled, gas-insulated, 275kV, 300MVA transformer (Tokyo Electric Power Company Shin-Sakado Substation) (Toshiba) Liquid-cooled, gas-insulated, 275kV, 300MVA transformer (Kansai Electric Power Company Hirakata Substation) (Mitsubishi) Liquid-cooled, gas-insulated, 275kV, 250MVA transformer (Chubu Electric Power Company Abe Substation) (Hitachi) Three-phase, 500kV, 1260MVA transformer (Kansai Electric Power Company Oi Nuclear Power Station) (Mitsubishi) Tertiary 50% capacity, single-phase, separate-winding, 512.5kV, 750/3MVA transformer (Tokyo Electric Power Company Shin-Okabe Substation) (Hitachi) Three-phase, 275kV, 1100MVA transformer (Tokyo Electric Power Company Higashiogishima Power Station) (Fuji)	Gulf War
Gas-insulated, three-phase, 155kV, 25.5MVA transformer (Chubu Electric Power Company Kitamatado Power Station) (Fuji) High-head-drop, self-cooled, gas-insulated, three-phase, 75kV, 20MVA transformer (Chubu Electric Power Company Tokadai Substation) (Fuji)	
Low-noise, 268.5kV, 300MVA,60dB transformer with no soundproof panels (Tohoku Electric Power Company Ishinomaki Substation) (Hitachi) New disassembled-for-transport type, three-phase, 275kV, 250MVA transformer (Chubu Electric Power Company Kita-Matsumoto Substation) (Toshiba) Forced-gas, forced-air cooled, gas-insulated, on-load tap changing, 66kV, 60MVA transformer (Tokyo Electric Power Company Toyosu Substation) (Toshiba) Single-phase, 525kV, 1500/3MVA auto- transformer using low-dielectric-constant PB (Tokyo Electric Power Company Shin-Sakado Substation) (Hitachi)	
1050kV, 1000MVA, UHV field demonstration testing transformer (Tokyo Electric Power Company Shin-Haruna Substation) (Hitachi, Toshiba, Mitsubishi) New disassembled-for-transport type, three-phase, 500kV, 300MVA transformer (Kansai Electric Power Company Okutataragi Power Station) (Mitsubishi) 500kV, 250MVA reactor (Electric Power Development Company) (Mitsubishi)	
Forced-gas, water-cooled, gas-insulated, 275kV, 300MVA transformer (Tokyo Electric Power	

Company Higashi-Shinjuku Substation) (Toshiba) Forced-gas, water-cooled, gas-insulated, 275kV, 150MVA transformer with shunt reactor (Tokyo Electric Power Company Katsunan Substation) (Toshiba) Forced-gas, forced-air cooled, gas-insulated, 161kV, 68MVA transformer (Tohoku Electric Power Company Yanaizu-Nishiyama Geothermal Power Station) (Toshiba) 2300kV testing transformer (Hitachi) New disassembled-for-transport type, 500kV, 1000MVA transformer (Chubu Electric Power Company Aichi Substation) (Mitsubishi) Three-phase, 500kV, 1450MVA transformer (Tokyo Electric Power Company Kashiwazaki-Kariwa Nuclear Power Station) (Hitachi) World's highest capacity moulded three-phase, 22kV, 13MVA transformer (Tokyo Metropolis) (Fuji) High voltage double rated, three-phase, 520(225)kV, 730MVA transformer (Kyushu Electric Power Company Reihoku Power Station) (Hitachi) 500kV, 250MVA reactor (Electric Power Development Company Sakaide Power Station) (Toshiba) Different capacity, three-phase, split-winding transformer 275kV, 800/450-350MVA transformer (Kansai Electric Power Company Himeji No. 1 Power Station) (Mitsubishi)	
Three-phase, 500kV, 1450MVA transformer (Tokyo Electric Power Company Kashiwazaki-Kariwa Nuclear Power Station) (Toshiba) Forced-gas, water-cooled, gas-insulated, three-phase, 107.5kV, 40MVA transformer (Chugoku Electric Power Company Shimada Substation) (Fuji)	Kobe Earthquake
New disassembled-for-transport type, 500kV, 1000MVA transformer (Chubu Electric Power Company Seibu Substation) (Toshiba) Three-phase, on-load tap changing, 275kV, 1050MVA transformer (Tohoku Electric Power Company Haramachi Power Station) (Toshiba, Fuji)	
New disassembled-for-transport type, three-phase, 275kV, 250MVA transformer (Chubu Electric Power Company Shin-Hokushin Substation) (Fuji) New disassembled-for-transport type, three-phase, 500kV, 800MVA transformer (Kansai Electric Power Company Okutataragi Power Station) (Mitsubishi) Fully transportable, three-phase, 281kV, 380MVA transformer for (maritime) power station (Tokyo Electric Power Company Chiba Power Station) (Fuji) 1H DC reactor for HVDC (Kii Channel Anan and Kihoku Converter Stations) (Toshiba, Mitsubishi) 1500/3MVA transformer for a 500kV underground substation (Tokyo Electric Power Company Shin-Toyosu Substation) (Toshiba)	

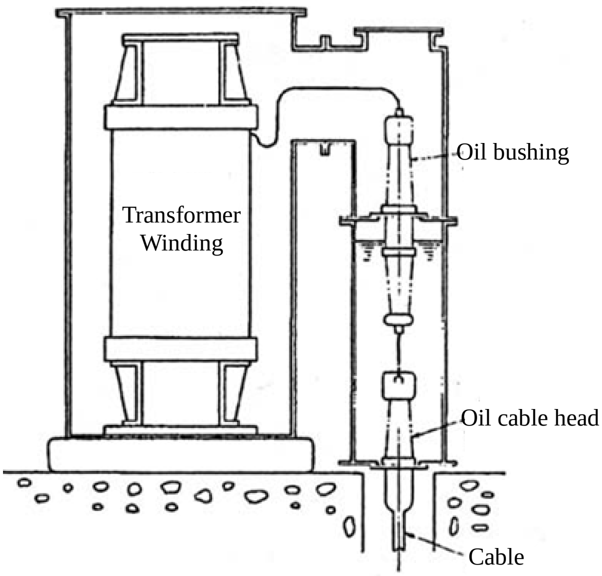
155/175MVA transformer for an arc furnace (IMEXSA, Mexico) (Toshiba) 152/182MVA transformer for an arc furnace (ANSDK, Egypt) (Toshiba)	
500kV, 872MVA transformer for HVDC conversion (Kii Channel Anan and Kihoku Converter Stations) (Hitachi, Toshiba, Mitsubishi) Liquid-cooled, gas-insulated, 275kV, 450MVA transformer (Chubu Electric Power Company Meijo Substation) (Hitachi)	
Split-winding, three-phase, 525kV, 410MVA transformer x 2 (Tokyo Electric Power Company Futtsu Power Station) (Fuji) Three-phase, 525kV, 1100MVA transformer (Electric Power Development Company Tachibana-wan Power Station) (Fuji) Single-phase, 765/400kV, 1500/3MVA auto-transformer (EDELCA, Venezuela) (Mitsubishi) Single-phase, 525kV, 120/3MVA shunt reactor with secondary winding (China) (Fuji)	
Special three-phase, 500kV, 1500MVA transformer (Kansai Electric Power Company Nose Substation) (Mitsubishi) New disassembled-for-transport type, 500kV, 1000MVA transformer (Chugoku Electric Power Company Chizu Substation) (Hitachi)	
High voltage double rated, three-phase, 525 (281.25)kV, 1060MVA transformer (Tokyo Electric Power Company Hitachinaka Power Station) (Hitachi)	New York terrorist attacks
Three-phase, 500kV, 1510MVA transformer (Chubu Electric Power Company Hamaoka Nuclear Power Station) (Mitsubishi)	
Forced-gas, water-cooled, gas-insulated, 345kV, 400MVA transformer (Australia) (TMT&D) Split-winding, three-phase, 507kV, 525MVA transformer x 2 (Tokyo Electric Power Company Kannagawa Power Station) (TMT&D)	Iraq War

■ Reference Materials 2: Explanation of Transformer Terminology

Reference Materials 2 provides illustrated explanations of transformer technology appearing in this report in order that this may be understood by non-specialists. Selected terms appear in the main text in italic font. These are provided for your reference.

Elephant Bushing

A method used to connect a transformer and a cable in oil within a duct. Given the possibility of differences in time spent onsite between transformer manufacturers and cable manufacturers, and also to clearly define the respective roles of each manufacturer, it is common in Japan to have transformer terminals connected to an oil-oil bushing and then connected to a cable within a duct. This type of oil bushing is called an elephant bushing because the shape of the duct resembles an elephant's trunk.



SF$_6$ Gas

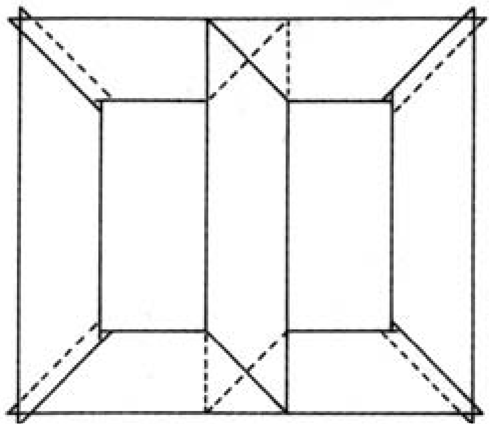
Recognised for its superior insulation properties in the USA in the 1930s, this was first used in gas circuit breakers. Its application in transformers was later examined and it was commercialised in transformers in the 1950s. It is widely used today in gas-insulated switchgear. While it is classed as a greenhouse gas, there is as yet no appropriate substitute for SF$_6$, so it is still used with the main countermeasure being to reduce the emissions into the atmosphere as much as possible.

Acoustic Corona Location

A system of estimating the location of partial discharge within a transformer where the partial discharge is accompanied by sound. The waveform of the sound is recorded using three or more microphones while also recording the waveform of the electrical partial discharge; the time difference between the sound waveforms and the electrical discharge waveform allow an estimation of the location of the partial discharge. Differences in the distance between the source of the sound and the microphones create differences in travelling time; altering the position of the microphones makes it possible to determine the location of the partial discharge quite accurately.

Frame-Shaped Core

A core structure that makes the most of the properties of grain-oriented silicon steel sheets; the sheets are cut at 45° angles and placed against the core limbs and yoke. The core is so named because the angle of the joins resembles a frame. The joins are alternately arranged with a 20-30mm deviation to ensure a smooth flow of magnetic flux.



Frame join

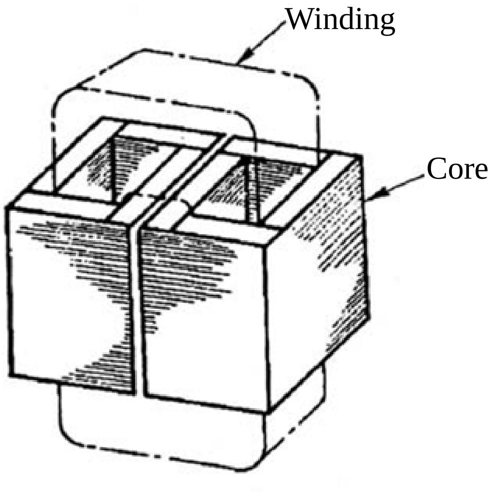
Voltage Application Test

A means of AC insulation testing for transformers, wherein a specified test voltage is applied to a winding in a test transformer.

Gas-Insulated Switchgear (GIS)

The general term for a device that makes up the circuit configuration within a substation, from the transmission line intake to the connection to the transformer, encompassing all non-transformer substation equipment (e.g. circuit breakers, arresters, disconnecting switches and current transformers) and the transformer connection busbar within a pressurised vessel.

Shell-Type Transformer
A structure widely used when transformers were first developed, wherein the windings were assembled first, then the core was wrapped around them. So named because the core is located on the outside.



Uniform Insulation
An insulation structure wherein the ends of the wire and the neutral point have the same insulation strength.

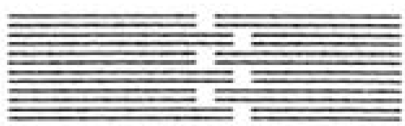
Vapour-phase-Drying Method
A method of drying the interior of a transformer, whereby the insulation is heated to expel its moisture content as quickly as possible. This drying method uses heat to facilitate the increase in temperature of the insulation by bring the vapour of kerosene, a type of lamp oil, into contact with the cold insulation, where it liquefies and transmits latent heat to the insulation. The liquefied kerosene is retrieved once heating is complete, and the insulation vacuumed in a furnace to evaporate and dry out any remaining moisture content.

Silicon Steel Sheets
Steel sheets developed in the United Kingdom in 1900 with superior magnetic properties; these are used to make cores for transformers and rotating machinery. Mixing around 3% of silicon with the steel produces a high magnetic flux density with a very small magnetising current. Since this dramatically reduces incurred loss, this contributed greatly to the upsizing of machinery following this invention.

High Grain-Oriented Silicon Steel Sheets
Developed in Japan in 1968 for transformers, these silicon steel sheets were designed to improve the amount of incurred loss by having the rolling direction aligned in a direction more susceptible to magnetisation of the crystal grains [100] than the existing grain-oriented silicon steel sheets; these are a high quality material currently in general use in transformers.

High Impedance
Transformers are represented in a circuit as impedance. Therefore, in the event of a ground fault, for instance, in the system, the fault current is limited by the sum of the transformer impedance and the system impedance, since the fault current flows through the transformer. Accordingly, where the system fault current is expected to be greater than the circuit breaker can handle, the transformer impedance is designated to be higher than normal. For 275kV devices, the impedance was usually designated as 14%; high impedance devices were designated as 20%.

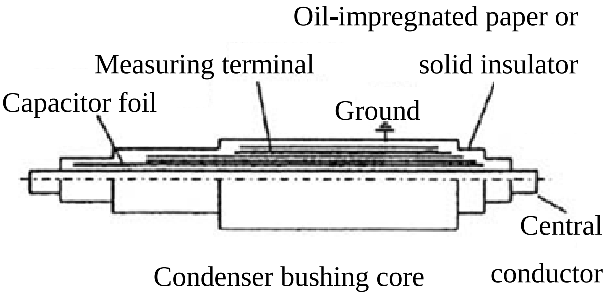
Alternately Stacked Joins
Frame-shaped cores are joined at the corners of the frame, usually with the joins on every alternate two steel plates 20-30mm apart.



Conservators
The purpose of conservators is to regulate volumetric change in transformer oil due to changes in temperature from a box located in the upper part of the transformer tank. Since hot oil can deteriorate in quality very rapidly when coming in contact with the air, a thin pipe is used to connect it to the transformer so that the oil temperature in the conservator does not rise too high. Using inert nitrogen as an intermediary layer or using a rubber membrane partition are ways to prevent oil coming into contact with the air, so as to avoid deterioration of the oil. Currently, the rubber membrane partition method is most commonly used in high-capacity transformers.

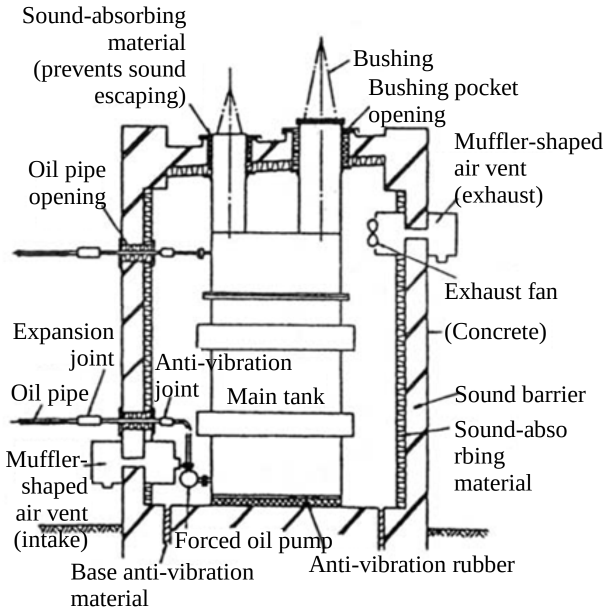
Condenser Bushing
Bushing is used as an intermediary for connecting the ends of the transformer winding protruding from the tank to the power source or the load. Condenser bushing is one such insulation structure commonly used for high voltages of 30kV and higher. This bushing has insulating paper wrapped around the central conductor, with multiple threads of capacitor foil weaved into it to control the potential. The potential distribution in the axial and radial directions can be controlled

by adjusting the size of the foil threads and the distance between them.



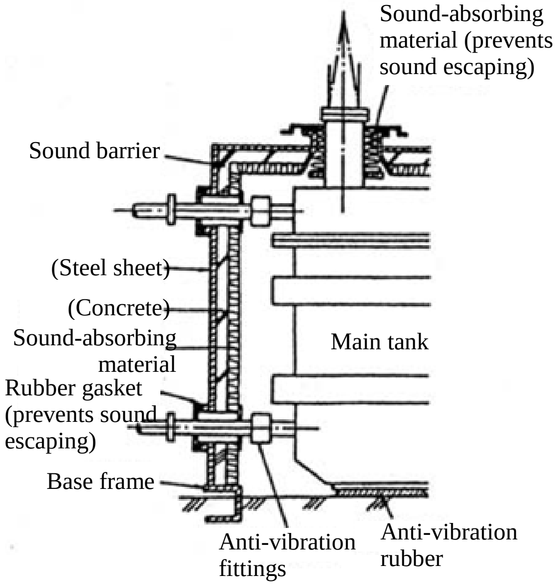
Concrete Sound Barrier

A sound barrier structure involving a transformer placed within a housing structure made of concrete, as shown in the figure, usually used when it is necessary to reduce transformer noise by 20dB or more. Consideration is given to letting no noise escape from the openings for the bushing pockets or oil pipes. Used less frequently more recently due to factors such as installation space and onsite work.



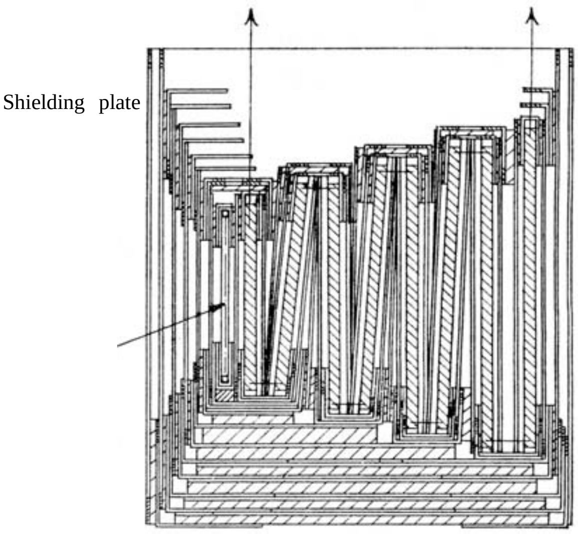
Concrete Panel Sound Barrier

A sound-proofing structure prefabricated by pouring concrete into a steel plate panel, which can then be mounted onto a transformer frame after the transformer has been installed. These can be expected to reduce noise by 15-20dB.



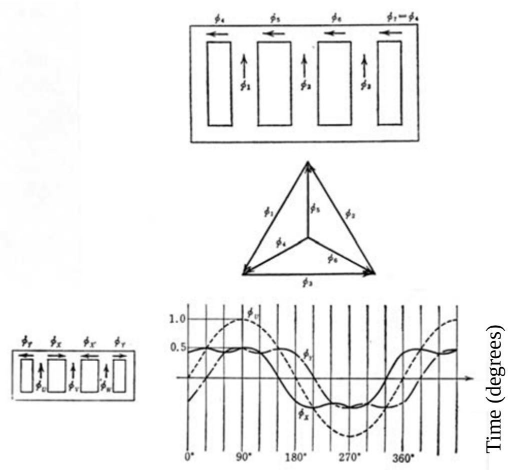
Surge-proof windings

A typical lightning-protected winding structure for shell-type transformers, having a large electrostatic shielding plate at the ends of the lines. It has the same properties as the multiple cylindrical windings for core-type transformers.

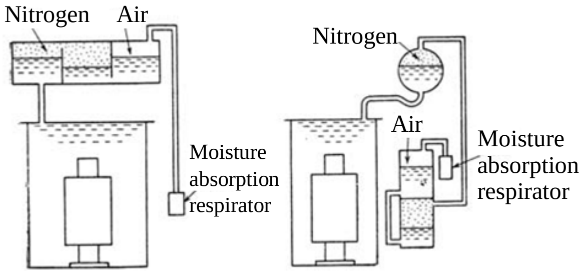


Three-Phase, Five-Leg Core

A structure in which the magnetic flux of the main legs (Φ_1, Φ_2, Φ_3) is divided between the yokes (Φ_5, Φ_6) and the side legs (Φ_4, Φ_7) so as to reduce the height during transportation. In terms of the magnetic flux sine wave, this can reduce the height of the yoke by $1/\sqrt{3}$. In fact, if the magnetic flux is given a constant density in order to superimpose harmonics onto the magnetic flux, the cross-section of the yoke can be reduced by up to 50%.



Three-Chamber Conservator
A type of nitrogen-filled conservator, so named because the inside of the conservator is divided into three parts, as shown in the figure. While the nitrogen-filled type was widely used initially, it had the major disadvantage of a large tank and it was gradually superseded by the floating-tank type.



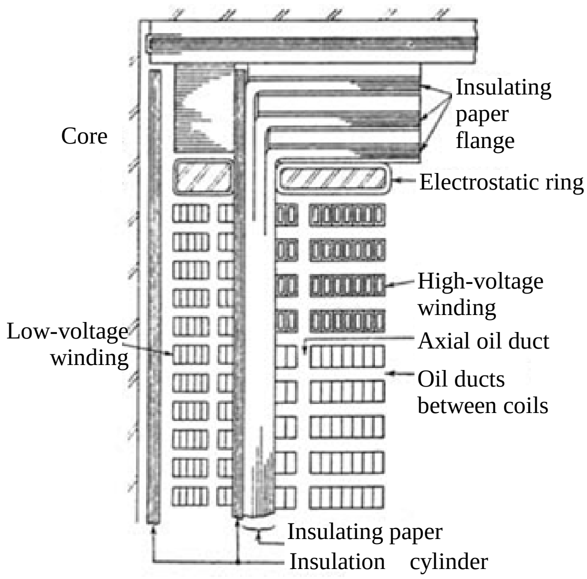
(b) Horizontal three-chamber type (a) Vertical three-chamber type

Magnetic-Domain-Refined Silicon Steel Sheets
High grain-oriented silicon steel sheets with the axial direction aligned with the direction of the rolling for ease of crystal magnetisation. To further enhance these properties, the surface of the sheets is divided into magnetic domains by using a laser to make fine cuts with very hard edges.

Vacuum Drying
A drying process to remove moisture content from the insulation as well as any moisture attached to the core, during which the contents of the transformer are heated with hot air and then the entire drying oven is vacuumed to hasten the extraction of moisture and to thereby reduce the drying time.

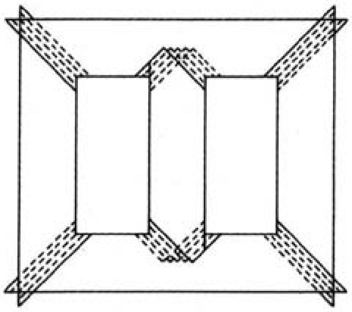
Arc Suppresion Test
A test when a transmission line has grounded through an arc to confirm whether sending the ground current through an arc-suppression coil connected to the neutral point has extinguished the arc current, returning it to 0, and eliminated the ground fault.

Main-Gap-Filling Insulation Structure
A structure within the insulation structure between the high- and low-voltage windings filled with highly insulating-strength solid insulation without any oil gap. The axial oil duct for cooling the windings is built within the windings. However, this method is currently hardly used, because it is difficult to construct windings with no oil gap and partial discharge may occur in these tiny gaps during testing in high electrical fields.

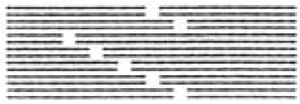


Degree of Polymerisation
A scale used in examining the deterioration of cellulose insulation material. Cellulose forms a long chain of hydrocarbons, which gradually breaks down through heat and reduces in molecular weight. The degree of polymerisation is a scale used to determine the extent of the reduction in molecular weight.

Step-Lap Joint
A joint structure joining the legs and yoke in such a way that the steel plate battens of the core sheets are arranged in a stepwise manner, as shown in the figure. This smoothens the flow of magnetic flux, which has the effect of reducing noise and incurred loss.

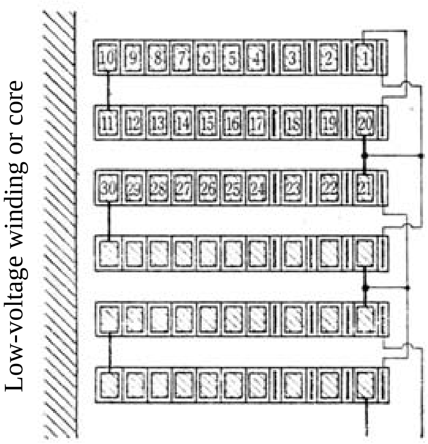


Step-Lap Joint



Insulation Coordination
Establishing appropriate respective protective equipment for transmission lines and machines connected to them, determining the level of protection and the appropriate reasonable level of insulation. Establishing lightning arresters near the in-points for transmission lines and near transformers and limiting the amount of lightning voltage to equipment. Designing equipment to withstand lightning surges of higher voltages than that controlled by the arrester.

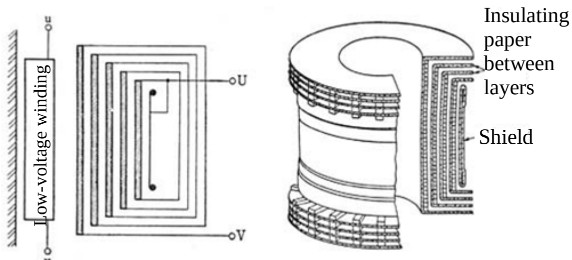
Damper-Shield Winding
A lightning-protected winding developed by Hitachi. A continuous disc winding with a shield conductor wound between each turn to improve the potential distribution, the winding has increased electrical capacitance between turns. The shield conductor potential is split into four sections and connected to the current-carrying conductor, which is split into two sections. Later named the CC shield winding with the discovery that the same effect is produced without the connection to the current-carrying conductor. Currently used mainly for 500kV-level windings.



Lightning-Protected Design

When lightning surges penetrate into a transformer winding, the voltage is very high and abrupt, throwing out the uniformity of the voltage distribution of the winding. When there is a low ratio between the electrostatic capacitance connected to the winding and the electrostatic capacitance to the ground, most of the voltage converges near the ends of the winding; historically, this was dealt with by reinforcing the insulation in this area. Various other methods were later proposed to increase the ratio and a structure was developed that could keep the voltage distribution as uniform as possible without reinforcing the insulation at the ends of the windings. This is what is meant by insulation design against lightning surges.

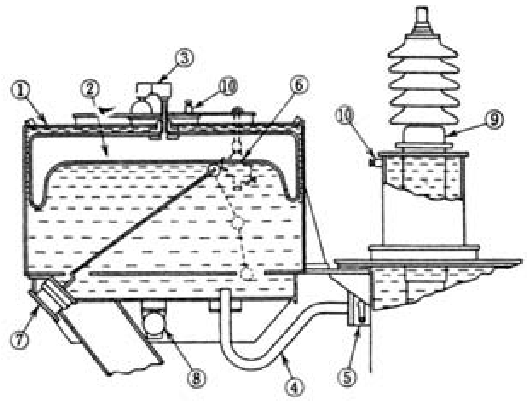
Multiple Cylindrical Winding (Non-Resonant Winding)
Coils are wrapped cylindrically around the insulating cylinder, with the oil ducts outside of them. Insulating paper is wrapped at the necessary thickness, followed by another cylindrically-wrapped coil; this is repeated for several layers, with the outer layer surrounded by an electrostatic shield at the same height as the coil and the shield connected to the lead at the end of the wire. Methods of connecting between layers include having a lead coming out and connected to the outer part, having the end of each internal layer coming through the oil duct and the insulating paper and onto the next layer, or having a tapering thickness in the insulating paper, where the next layer is wrapped the other way at the end of each wrap. The final two methods require varying thicknesses of insulating paper as the voltage is applied to two layers.



Tank Transported Sideways
Since the core surrounded the core and coil of shell-type transformers and could provide solid support for the interior within the tank, it was possible to support the mass of the core and coil during transportation even with the tank on its side. Some shell-type transformers were taller than they were long, so there were advantages to having them sideways in these cases. This method of transportation was adopted in the 1950s.

Diaphragm-Type Conservator

A type of conservator adopted in the 1960s, which separated the oil from the outside air with a nylon-filled rubber membrane or rubber pouch. Characteristically separating the oil and the air, this type of conservator is currently in standard use in Japan. The rubber membrane is embedded with a film of nylon or other substance to prevent air seeping through it. This means very little gas is dissolved in the oil; the gas-in-oil analysis currently commonly used for transformer maintenance has a very high degree of precision in analysing trace gases and has contributed to the discovery of abnormal phenomena.



(1) Oil expansion tank	(6) Automatic safety valve
(2) Air pouch	(7) Oil level gauge (with alarm contact)
(3) Moisture absorption respirator for air pouch	(8) Drain and filtering valve
(4) Connecting pipe	(9) Bushing support
(5) Valve	(10) Drain valve

Magnetic Tank Shielding

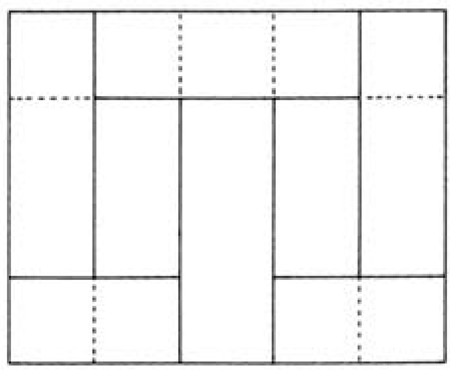
Magnetic shielding attached to the surface of the tank to prevent overheating and increased loss from leakage flux from the coil; a silicon steel sheet from several millimetres to around 30mm thick. The shield either comprises silicon steel bands with widths equal to the required thickness stacked on the coil at the appropriate width, with the cut edges spot welded together, or a 100-150mm wide silicon steel sheet the same height as the coil stacked to the necessary thickness and joined with epoxy or similar; these are then attached to the tank through various methods. The thickness depends on the amount of magnetic flux penetrating through the surface of the tank.

Auto-Transformer

A method of transformer connection. While transformers usually have separate high-voltage windings and low-voltage windings at the necessary capacity, auto-transformers characteristically have the high-voltage and low-voltage windings together. This achieves the same capacity as a double-winding transformer, where the high voltage capacity is equal to (high-voltage voltage – low-voltage voltage) x (high-voltage current) and the low voltage capacity is equal to (low-voltage voltage) x (low-voltage current – high-voltage current). By making these values equal and ultimately using a auto-connection in contrast to an ordinary transformer, high-voltage transformer capacity reduces to (high-voltage voltage – low-voltage voltage) / (high-voltage voltage). For example, if we compare a 500kV and 275kV single-winding transformer to one with separate windings, the transmission capacity is the same at (500-275)/500=0.45, requiring less than half the actual transformer capacity. This actual capacity is called self-capacity. Auto-transformers were universally adopted in Japan with the introduction of 500kV, because they cannot be used unless the system has the same ground network.

Right-Angled Joins

A core joint structure used until around the 1960s while hot-rolled silicon steel sheets were being used; the cores were joined together as shown in the figure.



Neutral Point

Where the ends of a three-phase winding are connected, the commonly-connected area where another end connects to the circuit through a star connection is called the neutral point. This area has a ground potential of 0.

Nitrogen-filled tank Conservator

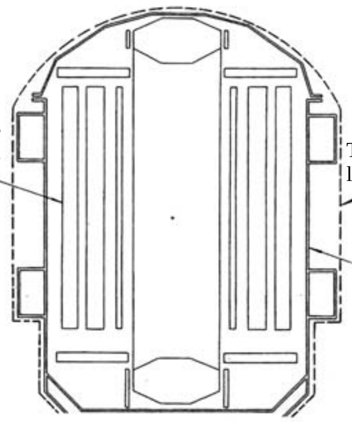
A conservator filled with inert nitrogen to stop the transformer oil coming into contact with the outside air, thereby preventing deterioration of the oil; there are three-chamber types and floating-tank types.

DC Bias Magnetism

The magnetic flux of a transformer core forms a sine wave that reflects the excitation current. This is usually positive-negative symmetrical and has no DC portion; however, when a DC current flows through the transformer winding from outside, the magnetic flux waveform becomes biased, with a phenomenon occurring in which the magnetic flux density increases to only one peak per cycle. This is called DC bias magnetism. In such a case, surges in the excitation current and increased noise and vibration occur, while the noise and vibration form a distorted wave with a lot of higher harmonics, due to positive-negative asymmetry in the magnetostriction of the core.

Rail Transport Limitations

Size restrictions for transporting freight by rail, limited by tunnels, signals and station platforms. While size and weight limitations vary according to the transport route, transportation is carried out by special freight cars according to a service planning diagram with special specifications in accordance with limited dimensions of a maximum width of 3.1m and a maximum height of 4.0m, as shown in the figure below.

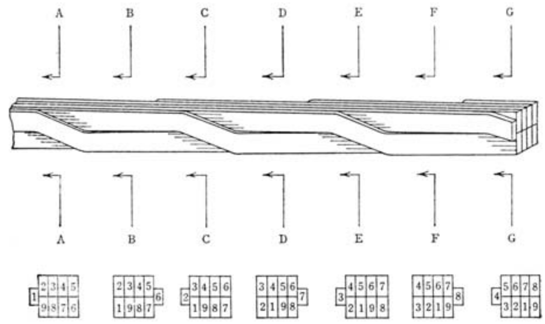


Voltage Phase Regulator (Phase Shifter)

Used to control the flow of electricity on a transmission line. Designed to shift the phase angle at the same time as the voltage. Voltage regulators act in phase with the main winding, while phase regulators generally regulate the voltage in quadrature to the main winding and alter the phase of the main winding by vector synthesis.

Transposed Cables

Transformer cables comprising an odd number of polyvinyl-formal-coated flat copper wires arranged in double file and twisted together at a pitch of around 10cm using a special machine to form a single bundled conductor, which is then insulated. Often used in high capacity transformers in order to reduce eddy currents loss caused by circulating currents generated by leakage flux from windings crossed to the conductor.



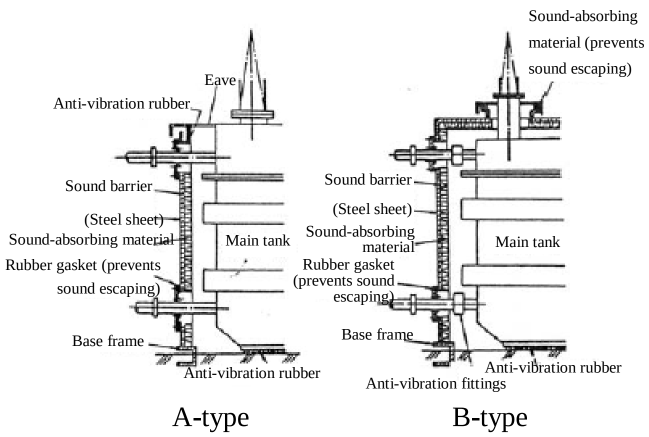
Cross-sections at each of the points A, B, C…

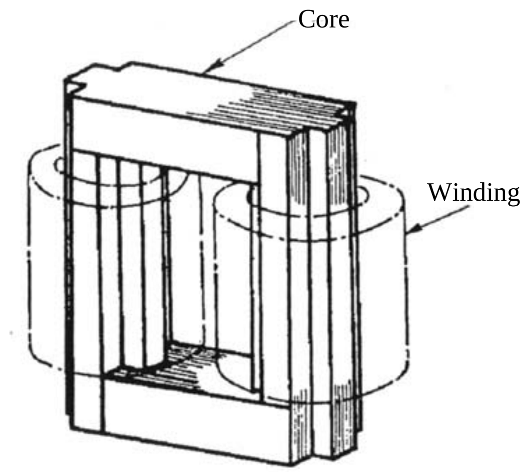
Electromagnetic Shielding

A magnetic shield attached to the surface of the tank in order to prevent overheating and increased loss on the surface of the tank due to leakage flux from the coil. A good conductor such as aluminium or copper is used on the tank surface; where magnetic flux occurs, a current passes through the shield to negate it, thereby repelling the magnetic flux. It prevents overheating and increased loss on the surface of the tank, which would be caused by the altered flow of leakage flux if the tank surface were used without a shield. Since the repelled leakage flux eventually enters the internal structure or core and increases the loss in that area, the shield has little effect on overall loss reduction. However, in the past, electromagnetic shields were used in high-capacity transformers as a means of preventing the tank from overheating from large current leads also.

Steel Sound Barrier

There are two types of prefabricated steel sound barriers, A-type and B-type. A-type covers only the tank and has a noise reduction effect of up to 10dB. B-type covers the entire transformer with steel panels and can reduce noise by up to 15dB.





<u>Extra-High Voltage</u>
Voltage of 10,000V or more.

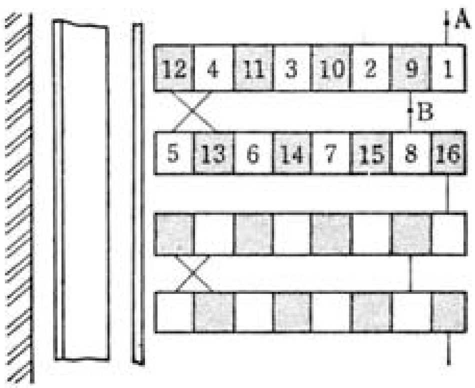
<u>Equivalent Capacity</u>
Used to express the capacity of multiple-winding transformers with three or more windings. Where the rated capacity of each winding is P1, P2, P3, etc., the equivalent capacity is obtained as follows.
P = (P1+P2+P3)/2

<u>Special Three-Phase System</u>
A method of easing transportation limitations by having a three-phase transformer composed of three separately-transported single-phase transformers, which are then each positioned as close as possible to a common base during installation under a shared top cover with a three-phase lead connection. Proposed in the 1950s, this system has often been used in Japan for transformers with unfavourable transportation conditions, such as underground substation transformers or hydroelectric power station transformers.

<u>Core-Type Transformer</u>
A transformer structure that has increased in worldwide adoption since first being adopted by US company GE in 1910 along with the barrier insulation method and is now used by most manufacturers. The core is assembled first without the upper yoke, then the upper yoke is assembled after the windings have been put on from above. So named because the core legs are concealed inside the windings.

<u>Double Concentric Winding Arrangement</u>
A type of core-type transformer winding arrangement, where either the high-voltage or low-voltage winding is divided into two and the other winding arranged concentrically between the two parts of the divided winding. The arrangement can be low voltage-high voltage-low voltage or high voltage-low voltage-high voltage. The divided winding is connected in series. Used as a countermeasure against leakage flux in high-capacity transformers because low-voltage, high-current lead-out is easier than in a concentric arrangement.

<u>High Series Capacitance Winding</u>
A lightning-protected winding developed by UK company EE. With a cleverly-designed conductor winding method to increase the electrostatic capacitance in series with the winding as a means of improving potential distribution, with the conductor rotated twice in two sections of the disc winding and having an adjacent separate potential conductor. Also used in UHV windings. Also called interleaved windings.

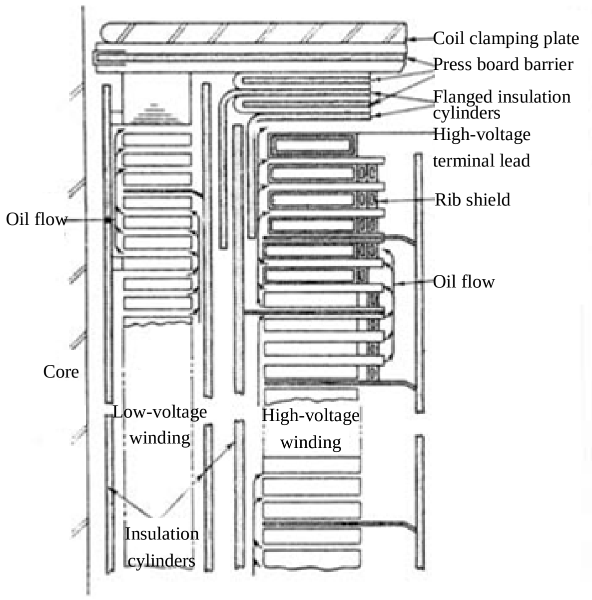


Perfluorocarbons

A non-flammable coolant used for cooling liquid-cooled, gas-insulated transformers, usually with a molecular formula of C_8F_{18} or $C_8F_{16}O$. With boiling points of 100-130˚C, these have no flash point, lower dynamic viscosity and higher density than transformer oil. Used as a transformer coolant because they are thermostable and are very compatible with other materials used in transformers.

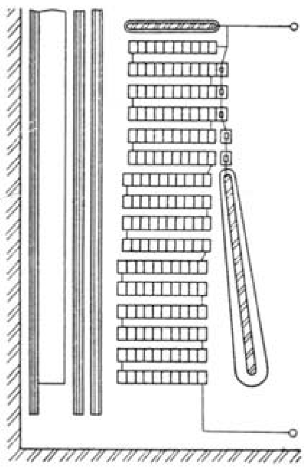
Barrier Insulation

An insulation structure used to improve the breakdown electric field of the oil gaps by having multiple insulation cylinders dividing the gap between the high-voltage winding and the low-voltage winding and alternately positioning the oil gaps and the insulation cylinders. Currently in standard usage.



Non-Resonant Transformer

A lightning-protected winding developed by US company GE with an electrostatic shield attached to the exterior of the winding so that its initial potential distribution becomes linear, thereby improving its potential distribution and increasing its series electrostatic capacitance. Characterised by a skirt-like shield called a stacked shield on the exterior of the winding.



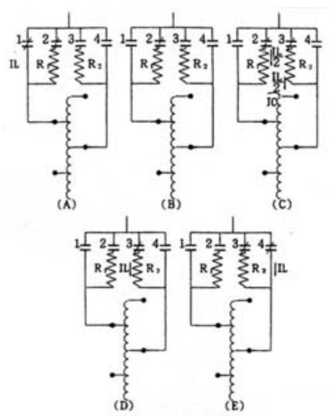
Non-Resonant Winding

A multiple cylindrical winding developed by German company AEG in the 1930s. So named because the winding has a high series electrostatic capacitance and a low ground electrostatic capacitance, meaning it has linear initial potential distribution.

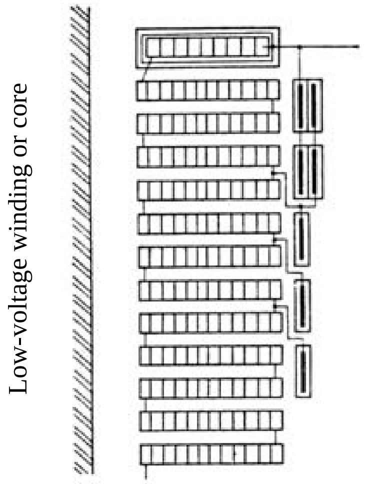
On-Load Tap Changer

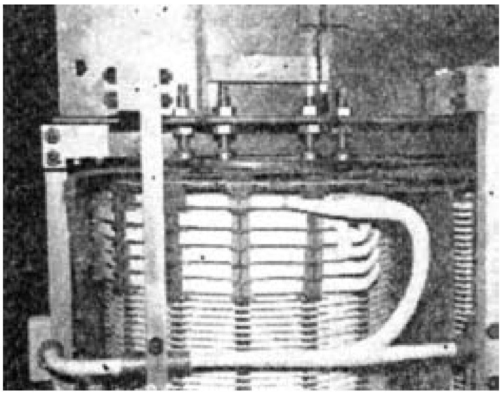
A method of voltage regulation by tap changing while a transformer is carrying a load; one such system has the tap winding incorporated into the transformer itself, while another system has a voltage regulating transformer in series with the main transformer.

There are two methods of supressing cyclic currents when the tap changer changing the taps bridges between taps while changing: one using a reactor and the other using resistance. The resistor type is currently more commonly used around the world because it is compact and can be built into the body of the transformer. As shown in the figure, the tap changing operation takes around two seconds to change. Since arcs can occur while the current is switching over, the change-over switch is housed in an oil tank separate from the oil used in the transformer itself.



Partially Shielded Winding
A structure in which the outer part of the coil near the ends of the wires is wrapped with an insulated shield conductor; also called a rib shield winding. The electrostatic capacitance between the shield and the coil is series capacitance, thereby improving the potential distribution near the ends of the wires.

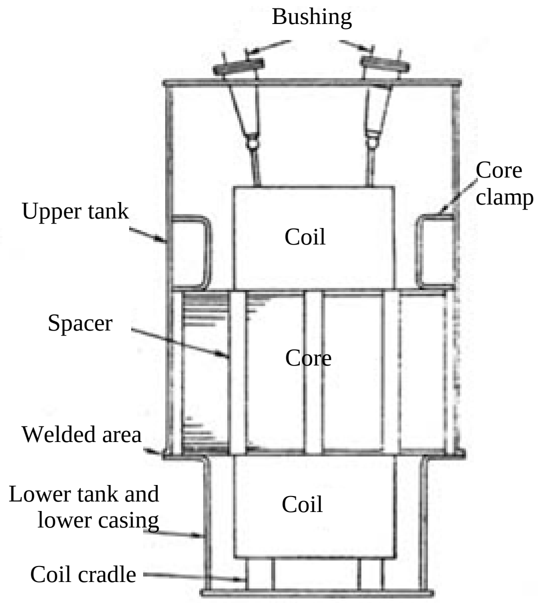




Partial Discharge
A state of partially deteriorated insulation accompanied by microdischarges, occurring when an electric field converges where electrodes are poorly shaped, when there is a void in the insulation or when there is dust or other foreign matter present. Partial discharge occurs at lower voltages than the voltage breakdown occurred. Partial discharge is viewed as a precursor phenomenon to transformer breakdown and there is a trend towards structures and operational procedures that do not generate partial discharge.

Shunt Reactor
A reactor placed between the system and the ground to create a leading load for electrostatic capacitance and an accompanying rise in voltage when long-distance high-voltage transmission lines and cables systems have a high ground electrostatic capacitance and a low load current. Shunt reactors are used to compensate for this and are mainly used during light loading. There are iron core shunt reactors and air core shunt reactors; the iron core type has less incurred loss and is currently used more commonly.

Form-Fit Tank
A shell-type transformer tank structure that minimises the space between the core and coils and the tank, wherein the core and coils are assembled on top of the lower tank and then the upper tank is put on top, with the tank itself also serving as a core clamp.



Grain-Oriented Silicon Steel Sheets
A commercial product based on the discovery that if the silicon steel sheets developed by US company Armco in the 1930s were cold rolled instead of hot rolled as they had been, and heat treated appropriately to decarbonise and recrystallize them, the direction of the edge susceptible to grain magnetisation would align with the rolling direction; with a little more rolling and heat treatment to roughen up the crystal grains, the amount of loss could be reduced.

Polychlorinated Biphenyl
A non-flammable transformer oil developed in the United States in the 1930s and widely used there due to its superior cooling properties and its insulation properties equal to mineral oil. It was also commercialised in Japan in the 1940s and used in transformers, but due to its toxicity production of it was banned in 1972 and use of it

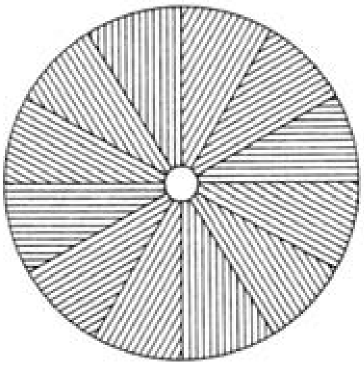
was banned in 1974. For transformers, it was used mixed with 40% trichloride benzol to lower its congealing point and viscosity. It was often used in condensers due to its large dielectric tangent.

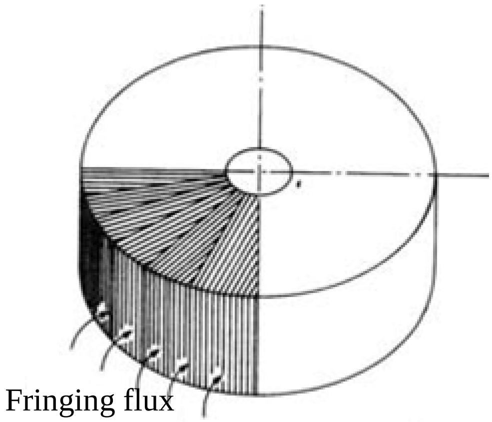
UHV Transmission
UHV is an abbreviation for Ultra High Voltage and generally refers to AC power of 765kV or higher. While 765kV transmission is in operation in various places around the world, 1000kV transmission started in the Kazakhstan region of the USSR in the 1980s and remains the only place in the world to have it operating.

Induced Withstand Voltage Test
A transformer AC insulation test, wherein a power source is connected to a low-voltage winding and induction of no more than twice the normal voltage is carried out on a test transformer, producing the voltage specified at the test terminal. This is done at higher frequency than that used for commercial purposes (usually 3-4 time higher) so as not to saturate the core. The potential of the terminals other than the test terminal is adjusted where necessary.

Oil-Impregnated Paper Condenser Bushing
A commonly-used type of condenser bushing that uses insulation paper at the core; once the condenser core is formed and dried, it is infused with transformer oil. Widely used up to UHV of 30kV or higher due to the stability of the insulation.

Radial Core
A core structure used in reactors, in which the core batten is arranged in a radial shape, as shown in the figure, with the effect of suppressing eddy currents resulting from core fringing flux generated in the gap.





Flow Electrification
A phenomenon in which the oil and insulation in forced-oil transformers generate frictional static electricity in the oil flow from the operation of the pump. The static electricity generated builds up a negative charge in the insulation and a separate positive charge in the oil. When the charge in the insulation goes beyond a certain limit, creeping discharge occurs, which intensifies until the AC insulation breaks down. Static electricity is most commonly generated near the oil intake at the lower part of the coil and is significantly affected by the shape of the flow path in this area. Electrostatic discharge also generally occurs near the oil intake at the lower part of the coil. While the positive charge in the oil dissipates with time, if a large amount is generated it builds up in the upper space; once a large amount builds up in the upper space, it generates a high voltage and develops into a discharge along the surface of the insulation in this area.

Resin Condenser Bushing
A type of condenser bushing that can either be a dry-type resin bushing, in which the condenser core is formed by impregnating the insulating paper with resin when the bushing core is moulded, or the resin can be vacuum-impregnated after the condenser core is moulded from insulation paper. The former is hardly used any more because of partial discharge occurring as a result of microscopic voids present in the core. These are now often used for oil-oil bushings because they are shorter and have smaller bushing pockets, since they do not require porcelain insulator.

■ Appendix

An outline of the intended applications for transformers and their classifications.
The intended applications for transformers can be categorised in the following six ways.
A. Voltage/current conversion
B. Input/output circuit isolation, polarity reversal
C. Using and converting impedance values
D. Voltage/current regulation
E. Surge transfer, noise suppression
F. Power distribution

Transformer classifications can also be categorised by intended usage as follows.

1. Power transformers
   All intended applications from A to F.
   Power Transformers
     (Power transmission transformers)
       Power station transformers
       Substation transformers
     (Distribution transformers)
       Secondary substation transformers
       Pole-mount transformers
       Underground transformers
       Pad-mounted transformers
   Industrial transformers
       Power-receiving transformers
       High-current transformers
       Semiconductor power conversion transformers
       Traction transformers
       Vehicle transformers
   Medical transformers
       Power transformers
   Consumer transformers
       Power transformers

2. Insulating transformers
   Intended applications A, B, C and E. Connected to a circuit to eliminate noise caused by potential difference, in turn caused by interlinkage magnetic flux in the circuit; used to ground the circuit at one point.

3. Grounding / arc supressing transformers
   Intended application is C, impedance use. Grounding transformers are used to provide a neutral ground point in the circuit; arc suppressing transformers are grounding transformers combined with a secondary reactor and used for the same purpose as arc suppression coils.

4. Starting transformers
   Intended application is C, impedance use. Used to start electric motors smoothly.

5.Testing transformers
   Intended applications are A and D, voltage/current conversion and regulation.

6. Instrument transformers
   Intended application is A, voltage/current conversion.

7. Leakage transformers
   Intended application is C, impedance use. Used when a large leakage reactance is required to provide a load with negative voltage/current properties, such as arc welding or neon tubes.

8. Induction voltage regulators, phase shifters
   Intended applications are A and D, voltage/current conversion and regulation. Changes the positional relationship of the primary and secondary windings by rotation and continuously varies the voltage or phase of the secondary winding.

9. Communication transformers (pulse / signal transmission)
   Intended applications are A, B, C and E. Used for voltage, current, and impedance conversion, polarity reversal, potential separation between circuits, conversion of balanced-unbalanced circuits, etc. during signal transmission using transformer circuit constants based on conversion characteristics, inductance and electrostatic capacity.

10. Noise/high frequency suppression / switching / lightning protected transformers
   Intended applications are B and E. Used to significantly reduce surges from the supply circuit and the transfer of noise to the secondary side.

The purposes of each transformer and the main technologies applied are summarised as a technology chart in the appended figure.

There are other ways to categorise transformers, such as:
   Classification by installation site
   Outdoor
   Indoor
Classification by cooling and insulation medium
   Oil-immersed
   Dry-type
   Gas-immersed
Classification by manner of voltage regulation
   Terminal block tap changer
   No-voltage tap changer

On-load tap changer
(On-load) voltage regulator
Classification by operating principle
Two-winding transformers, multiple-winding transformers
Auto-transformers
etc.

As will also be seen from the above study, power transformers are technically related to everything; it is a field that has attracted much interest for a long time and has played a leading role in technology. Accordingly, the author selected power transformers for the present systematic examination.

Appended Figure: Transformer Technology Chart

Purpose	Transformer Classification	Main Technology
A. Voltage/current conversion B. Input/output circuit isolation, polarity reversal C. Using and converting impedance values D. Voltage/current regulation E. Surge transfer, noise suppression F. Power distribution	1. Power transformers A, B, C, D, E, F I, II, III, IV, V, VI, VII, VIII, IX 2. Insulating / lightning protected transformers A, B, D, E II, IV 3. Grounding / arc supressing transformers C V 4. Starting transformers C V 5. Test transformers A, D II, III, IV, IX 6. Voltage transformers A I, II, III, IV 7. Leakage transformers C I, V 8. Induction voltage regulators, phase shifters A, D I, II, VII 9. Communication transformers (pulse / signal transmission) A, B, C, E I, II, IV, V 10. Noise/high frequency suppression / switching / lightning protected transformers B, E I, II, IV, V	I. Core structure and magnetic properties II. Winding structure, connections III. Insulation material and insulation properties IV. Surge properties V. Impedance and leakage flux VI. Cooling and heating VII. Voltage regulation VIII. Electromagnetic mechanical force IX. Transportation

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