Transforming history

The ABB power transformer story

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Imagine for a moment, a world without power transformers: It would be a world without high-voltage transmission systems and there would be no means to economically transport electric power over long distances. Power supply infrastructure would have neither the economies of scale nor the pooling of reserves that it enjoys today. More recent developments that would not have occurred include international power trading and the large scale tapping of wind power in remote regions, with their respective benefits for customers and the environment. Growing concerns over grid reliability additionally reflect the need for transformers of sufficient capability and robustness. Without the transformer, electrical power today would be less reliable, more expensive and more wasteful, and industries and homes would look quite different.

Through practically all the history of commercial transformers, ABB and its predecessor companies have been at the forefront of their manufacturing and ongoing development. In this article, ABB Review traces some highlights of this development.

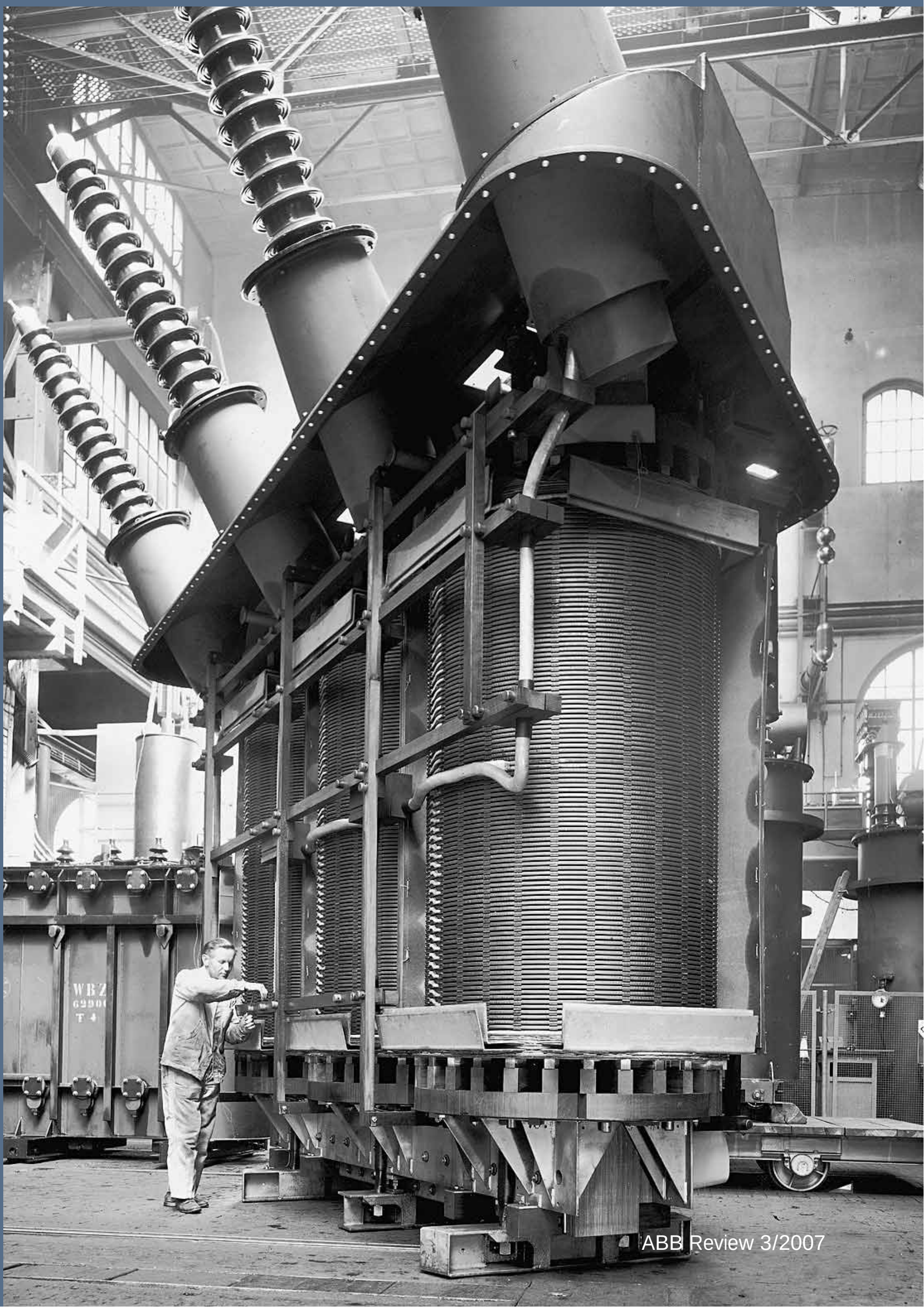

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ABB has always been well positioned to meet the demands of the power transformer market, ranging from single pieces of equipment in point-to-point transmissions to vital ingredients of interconnected power systems sprawling over vast areas.

Power and voltage development

At the end of the nineteenth century, the transformer proved itself an indispensable component for competitive transmission of electric power. A 20 kV setup was demonstrated at the electrotechnical exhibition in Frankfurt am Main in Germany in the year 1891, proving the feasibility of power transformers. Two years later, ASEA, one of ABB's parent companies, supplied one of the first commercial three-phase transmissions in Sweden – from a hydro power plant to a large iron ore mine some 10 km away.

Transformers made it possible to generate electric power at low voltages and then transform it to a higher level at which transmission incurs considerably lower losses, and finally transform the voltage back to a safer level at the site of consumption.

Transformer manufacturing emerged in most countries in Europe and in the USA. ASEA, BBC, General Electric, Westinghouse and other companies rapidly gained expertise in the manufacturing and installation of transformers 1. At the time, these were all domestic companies with technology of their own serving local state-controlled utilities in tight partnership.

Countries such as Sweden with practically no domestic fossil fuel reserves but ample potential for hydro power – albeit remote from the user – were especially eager to make use of electric power transmission. As transmission distances increased, the transmission voltage had to rise to keep losses down and to reduce the number of lines needed in parallel.

In the early 1950s, Sweden commissioned the world's first 400 kV transmission with a length of about 1000 km and 500 MW capacity. This breakthrough in voltage and capacity set a new standard in Europe 2.

This extra high voltage (EHV) strained not only the design and manufacturing capacity but was also a challenge in testing. Long transmission lines presented a risk of transient voltages. New and more stringent test procedures had to be established for the dielectric integrity. These new tests were then incorporated into the acceptance tests of the transformers.

Soon much of Europe was following Sweden's lead in adopting 400 kV EHV. The Canadian province of Quebec had a similar situation to Sweden, with limited fossil fuel but abundant hydro power, and large geographic distances between these and industrialized areas. Even higher voltages were needed to make efficient use of these power sources. In the second part of the 1960s, the power company Hydro-Québec introduced 735 kV transmission (a level later called 800 kV).

In the early 1950s, Sweden commissioned the world's first 400 kV transmission with a length of about 1000 km and 500 MW capacity.

1 An early three-phase transformer built to a patent of Johan Wenström patent, the technical genius of the early years of ASEA. Wenström called his transformer triple-converter

2 The Harsprånget 400 kV generator step up transformers: Single-phase units with three low voltage windings to serve three generators in parallel, each generator rated 105 MVA

In the USA, the building of large thermal power plants gathered pace, with plants reaching block sizes of 1000 MW and more. For such large plants to be viable, the power had to be distributed over long distances covering vast areas. A 765 kV system was therefore introduced in addition to an existing 345 kV system.

While 765 kV systems were being built, existing 500 kV systems were being extended. One example of development work on large interconnection transformers concerned the early 400 MVA single phase units rated 500/161 kV that were delivered to Tennessee Valley Authorities, TVA.

The first deliveries from ASEA in Ludvika for this purpose used a five-limb core with three limbs wound in parallel. Later, the number of wound limbs was reduced from three to two for the same rated power. Finally the last delivery to the same specification was built with one wound main limb and the voltage regulation part on one of the side limbs. On all these transformers, the high and low voltage windings were separated; ie, there was no auto connection.

In addition to saving man-hours in manufacturing because of fewer wound limbs, the transition from the earlier to the later design reduced the total dry mass by a quarter. Also the total losses (no-load and load losses)

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3 The 1785 kV UHV transformer installed at the AEP-ASEA test station outside South Bend, USA. The transformer is installed on an insulated platform to study the effect of line voltages up to 2200 kV phase-to-phase

4 1000 kV test setup with transformer and shunt reactor at ENEL research station in Italy

5 One of six converter transformers installed at the receiving end of the Pacific intertie transmission serving the Los Angeles area

were reduced by about 20 percent. After completion of these deliveries, the customer started to acquire and install auto-connected transmission transformers whose specifications were otherwise the same.

In the early 1970s, TVA commissioned its first 1200 MVA power plant at Cumberland, Tennessee. ABB Ludvika built the generator step-up transformers (rated 420 MVA) to a single-phase design. These transformers represented a technical breakthrough in terms of power capacity on one wound limb.

At the same time, ABB Ludvika launched a development program together with American Electric Power, AEP, – the largest private power company in North America – with the aim of finding the highest technically feasible transmission voltage. For this purpose, ABB built a full-size single-phase network transformer whose highest voltage was 1785 kV, rated at 333 MVA. The transformer had one wound limb, and with a core extended to three wound limbs on a five-limb core, the capacity would have been 1000 MVA per phase; ie, a total capacity of 3000 MVA for a complete three-phase bank. The transformer was installed and operated at the research facility jointly run by ABB and AEP. The transformer served successfully until completion of the research program 3.

Similar development programs were also embarked upon by some of ABB's other predecessor companies – aiming to achieve transformer designs capable of handling transmission voltages of 1000 kV and above. One example is a full-size transformer and shunt reactor built in Italy for 1000 kV and installed at ENEL test station Suveto 4.

Changing patterns in power production and grid build-up deferred the move to still higher transmission voltages and extreme transformer capacities. Voltages higher than 400 kV in Europe and 800 kV on other continents have so far not been commissioned for commercial operation. The need for high capacity, long distance transmission – eg, to reach large and remote hydro power stations – has resulted in renewed interest for voltages in the range of 1000 to 1200 kV in China and India.

Transformer types

The majority of transformers are built on the core type concept – a concept that today can be described as cylinder-shaped windings arranged concentrically on a cylinder-shaped core. An alternative design concept is the so-called shell type concept where the windings have a rectangular shape and segments of low and high voltages are more or less interleaved. For certain applications the shell type concept has found a viable position; eg, large generator transformers with special requirements. The large difference in production techniques for the two designs makes it feasible to have different workshops for the two concepts. ABB has therefore allocated the production of most of its shell type transformers to its factory in Spain.

Restructuring of manufacturing footprint

Power transformers were previously considered to be more or less strategic products, and several countries deemed it important to have domestic manufacturing capacity. Thus ASEA established close ties with existing transformer manufacturers and established new factories in several countries such as Germany, South Africa, USA, Canada, Norway and Brazil. BBC, with transformer factories in Germany and Switzerland, established a factory in Brazil. Westinghouse supported the build-up and provided know-how to factories in Italy, Spain and Australia.

Power transformers are complex "engineered-to-order" products requiring competence and experience in engineering and manufacturing. Such a business should be built up around defined instructions which are reflected in tools in engineering and production.

In order to make efficient use of available resources, design and production methods were unified for all factories within the group. ASEA's Ludvika factory served as a technical resource and gave advice and support on technical and manufacturing issues. Once a year – or more often when needed – the technical and manufacturing managers met for an exchange of information and to learn the latest news on development work. Engineers from the different companies were often invited to Ludvika for training and education, and highly skilled Ludvika engineers were given the opportunity to serve in leading positions in the individual companies.

Design rules and manufacturing procedures were documented in special standards or instructions covering individual phases in the process of building transformers. This way of working made it possible to accumulate substantial experience in each phase of the design and manufacturing of the power transformer. The large total production base additionally made it possible to maintain and support a comprehensive development team.

The close cooperation between the individual manufacturing units continued after the forming of ABB. All participating units were given access to common information and support from all employees within the ABB group. The IT tools used in design and engineering are now the same around the globe.

Long distance transmissions

For improved utilization of existing lines and rights of way, three types of equipment have emerged: HVDC converter transformers, phase-shifters and shunt reactors.

HVDC converter transformers

Transmission with HVDC has several advantages when it comes to long-distance transmission. The mode was first used on long cable transmissions to reduce the need to mitigate the excessive voltage build-up along the cable caused by reactive power in an a.c. transmission. In HVDC transmissions, the power transformer not only modifies the voltages to permit power to be exchanged between the a.c. and d.c. systems; it also transforms the a.c.-voltage from a three-phase system to a six-phase system. This permits the harmonics generated by the valve currents to be reduced. Furthermore, the transformer acts as a barrier for the d.c.-potential, preventing d.c.-voltage from entering the a.c.-system. Current harmonics from the valves and d.c.-potential applied on the valve side of the transformer implied new technical challenges for the transformer engineer. The harmonics give rise to additional losses, which need to be taken into account and minimized to avoid dangerous local overheating in the transformer. The d.c.-potential on valve windings results in a dielectric stress pattern different from the stresses generated by the normal a.c.-voltages.

> Several transformer technologies as well manufacturing plants and procedures had to be unified within the shortest possible time – and this without lessening the momentum of normal production.

The design of the modern converter transformer has its origin in the units built for the Itaipu project in Brazil in the 1980s. A d.c. transmission voltage of 600 kV was achieved with two series-connected converters. In this means of connection, the transformers for the upper bridge must be capable of a dielectric withstand of 600 kV. There are a total of 24 single-phase converter transformers at each end of the HVDC transmission, with a total capacity of 6000 MW. The transformer is built as a single phase unit with two valve side windings, one for delta connection and the other for wye connection (both being needed to reach the necessary phase split). The two valve side windings are built on separate limbs on a common core and act electrically as two independent transformers[1].

In 2004, ABB delivered single-phase units with a rating of 620 MVA to the Pacific Intertie (USA) for a d.c. transmission voltage of 500 kV 5. These are the largest converter transformers manufactured so far.

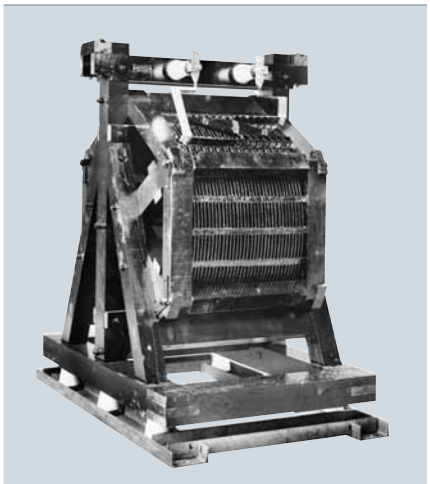
Presently ABB is in the final stage of the development of converter transformers for 800 kV d.c. transmissions[2]. Long point-to-point transmissions, especially in China and India, stand to benefit from the use of higher voltages than are currently available. The environmental advantages lie in the lower transmission losses and the reduction in land use for the right of way.

The phase shifter

The power flow in highly meshed high voltage transmissions needs to be controlled to achieve an efficient load distribution between power lines in parallel. The load in the individual

6 400 kV quadrature booster with a throughput capacity of 1630 MVA, installed in the Italian network for power control of the interconnection between Italy and France

7 A reactor from 1923, built for short circuit protection and control



Footnotes

1) Parallel to the HVDC transmission, an 800 kV a.c.-transmission runs from Itaipu to the Sao Paolo area – this was mainly built by the BBC factory in Mannheim.

2) See also Asplund, G., Ultra high voltage transmission, Alternative scenarios for long distance bulk power transmission – 800 kV HVDC and 1000 kV HVAC, *ABB Review* 2/2007 pp. 22–27.

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lines is governed by the phase displacement between the nodes in the transmission system. A phase-shifter provides a means to control this displacement and thus the load flow.

Such a phase-shifter is installed in series with the power line and has an outgoing voltage equal to the incoming voltage but with a (variably) shifted phase angle. With only a limited need in phase-angle shift, the complexity of the phase-shifter can be reduced to produce a quadrature voltage only and the apparatus will be called a quadrature booster 6. Physically a quadrature booster is built as two transformers: one magnetizing unit and one series unit[3)].

The shunt reactor

The reactor (sometimes called inductor) is not a transformer in the sense of a device transforming power from one voltage level to another, but its similarity in construction and manufacturing makes it a highly suitable product for a transformer plant.

The reactor found its application in the early part of the last century as an efficient piece of equipment for the control of overcurrents and thus short circuit protection 7.

Long-line transmissions as well as extensive cable networks on high voltage generate a substantial amount of reactive power. If not balanced, critical voltage rises develop during low loads. A reactor (the shunt reactor) installed between the power line and earth provides an efficient means to control and balance such reactive generation. Essentially, the shunt reactor acts as a sink for reactive power.

Repairing an HVDC transformer in Drommen, Norway

8 A 150 Mvar shunt reactor in the Swedish 400 kV grid

9 An air-cooled rectifier transformer rated 91.74 MVA

The modern shunt reactor was introduced in the late 1960s using components and technology from the core type transformer 8.

The design of the modern converter transformer has its origin in the units built for the Itaipu project in Brazil in the 1980s.

Industrial transformer

A substantial segment of the ABB product family is made up of large transformers for industrial applications, such as furnace transformers and rectifier transformers 9. These transformers are characterized by the comparatively low voltage on the secondary side – but have appropriately high currents. Load currents of 60 kA or more are not unusual. These high currents with their high harmonic contents pose significant challenges, especially in terms of high magnetic fluxes around exit leads within the tank and around the airside part of the leads.

In furnace transformers, the high currents are accompanied by frequent short circuits during the initial phase of the heating of the steel in the melting pot. The resilience to such short circuit forces and the requirement for large regulating ranges call for special care in design and manufacture.

Forming ABB

In August 1987, the Swedish ASEA and the Swiss-German BBC decided to merge and jointly form the ABB company. Shortly afterwards, ABB was also able to acquire the transformer manufacturing segments of Westinghouse in the USA, Ansaldo in Italy and Spanish factories. The National Industry in Norway and the Finnish Strömberg had become part of ASEA just before the merger.

In fact, ABB can today, through its various predecessors, claim the combined experience of 700 years of transformer manufacturing Factbox. Several transformer technologies as well manufacturing plants and procedures had to be unified and made to work together within the shortest possible time – and this without lessening the momentum of normal production. This was truly a gargantuan task.

A number of task forces and R&D groups were established to evaluate the individual technologies and to select the most viable ones. Although the principle of transformer technology is universal, there are many differences in the fine-tuning. Major objectives were lower costs, shorter production time, and higher quality measures in terms of test room failures. It was important to package all design and production variables into a seamless engineering IT system supporting customized engineering and manufacturing.

ABB succeeded in unifying its technology, and today offers the same product and high standard of quality wherever the transformer is manufactured, be it in Germany, Canada, Brazil, India or China. Power transformers are expected to deliver reliable service for 30 to 40 years in all types of networks.

Several of the participating manufacturing plants needed substantial renovation and modernization to fulfill the ABB standard when it came to cleanliness and competence for building transformers meeting today's requirements. Many new greenfield investments were made permitting a quick ramping up of production using this common technology base and with substantial help from engineering support teams. ABB established an engineering training school in Germany: the Knowledge Communication Center.

The increased manufacturing volume resulting from the formation of ABB made it possible to initiate several development programs, including the exploration of innovative transformer designs. Studied design concepts included superconducting transformers (a 630 kVA saw one year of service) with HTSC[4] winding conductors, high voltage foil-wound windings (three units in service), large dry and air-cooled windings based on cable technology (two units in service). By embarking on these and similar more or less speculative projects, ABB has acquired a vast quantity of knowledge that it also applies to conventional transformer technology. And even if

Factbox TrafoStar™, 700 years of pedigree

ABB can today look back on the combined experience of 700 years of transformer manufacturing, having inherited designs and expertise from the following companies:

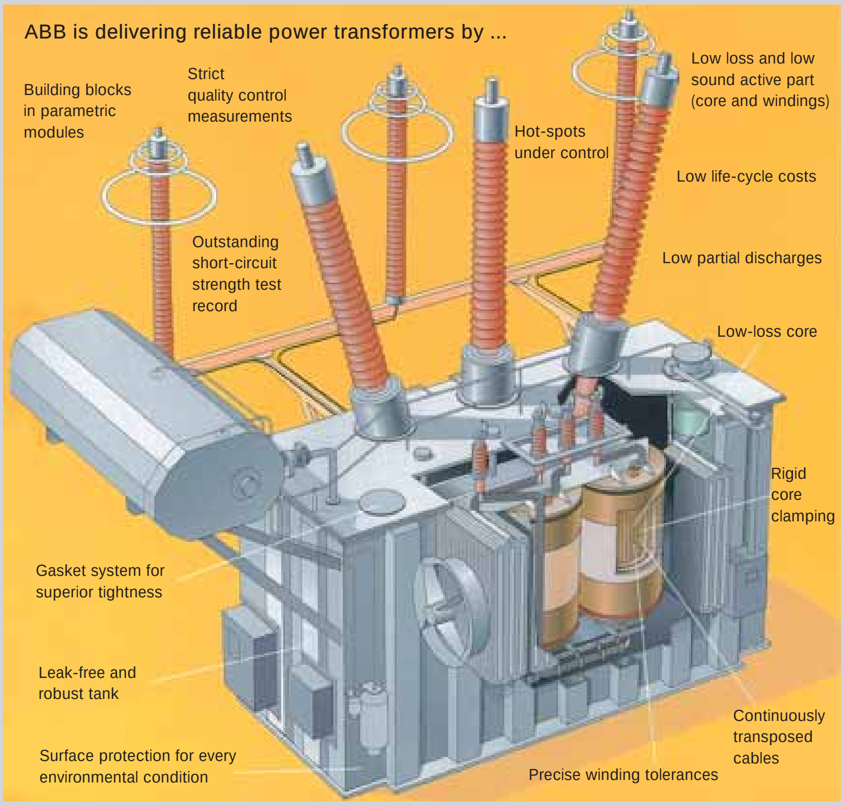
- Asea
- Ansaldo / Ital Trafo / IEL / OEL / OTE
- BBC
- GE, USA
- National Industri
- Strömberg
- Westinghouse
- and more …

These 700 years reflect the knowledge ABB has of different technologies in transformer design and manufacturing, combined with service experience in the networks around the world.

ABB draws on this considerable knowledge-base and combines the best practices of its predecessors in its global, common business concept: TrafoStar™-platform.

Each TrafoStar™ transformer follows common engineering, supply chain and manufacturing rules. A modularized construction allows a high level of re-use, reducing factory throughput time, while minimizing variation and achieving highest quality. The production of 1400 units a year provides a base for a unique performance and key parameter analysis, permitting continuous improvements in all plants.

ABB's customers do not benefit only through the new transformers the company delivers. The broad knowledge base, now documented in the TrafoStar™ concept, permits ABB to provide service and support on all 400,000 power transformers now in service around the world.



Footnotes

[3] A quadrature booster uses a shunt transformer to phase-shift the supply voltage by 90° (hence the term quadrature). The output of this shunt transformer is tapped, permitting the amplitude to be varied. A series transformer is then used to add this to the main circuit.

[4] HTSC: High Temperature Superconductor

the market has still not fully accepted these innovations, the solutions are available.

In view of the total capacity of the newly formed ABB, the transformer segment could continue its predecessor's active participation in international bodies such as CIGRÉ, IEC and IEEE. This participation has made it possible to establish standards on test levels and test procedures to verify transformer integrity under various operational conditions. The application of stringent quality requirements in design and manufacturing has reduced the risk of unforeseen operational difficulties during a long service life.

More than the sum of its parts: assembling a transformer

10 An ABB distribution transformer in Brazil

After the merger, ABB had developed a range of transformers covering the full transmission chain, from generation to the outlet socket in the residential home. The transformers used in the last steps of this chain are generally called distribution transformers. These transformers are more or less bulk products built to suit the network topology in each individual region of the world 10.

ABB makes full use of its knowledge and capacity in developing and manufacturing strategic transformers materials and components in special plants. In this respect, high quality products such as transformer boards and winding insulation kits manufactured according to the company's own technology must be mentioned. ABB is also one of the world's major suppliers of all types of tap changers and bushings. The company's own technology in transformers, insulation materials, tap changers, bushings and up-coming transformer electronic control places ABB in a unique position in being able to offer a complete product portfolio in transformers and provides a strong basis for future development.

In the late 1980s and 1990s, expansion and build-up of generation and transmission slowed down in the western world while new ABB factories were established in China and India.

Geographical shift in production

The impact of the formation of ABB was largely limited to Europe, where most of the transformer manufacturing plants were located. Later on, acquisitions on the North American continent followed.

However, in the late 1980s and 1990s, expansion and build-up of generation and transmission slowed down in the western world. The existing capacity was more or less sufficient for covering demand. The abundant availability of oil reduced the need to convert energy supplies into electricity. This led to overcapacity in the power transformers market.

At the same time, the economy in the Pacific Rim as well as in the Far East picked up and the need for electric power surged. Transformer plants in Europe and North America had to close while new ABB factories were established in China and India.

What about the future?

Transformers based on the induction principle will remain the base of voltage conversion for many decades to come. Changes in the materials used will help reduce both costs and better control of thermal capability. These developments will affect conductor materials as well as solid and liquid insulation materials; however, no substitutes for the electrical steel and the transformer core are in sight.

In the future, new ways of rating transformers through better control of the thermal capability will help reduce the use of expensive materials. Transformer specifications must evolve to place more emphasis on the load profile, future growth and emergency loadings – with the hottest areas for aging being covered by new standards. The new ways in which such international standards will rate transformers will require the integration of more intelligence. Other goals are to further increase the mechanical, thermal and dielectric integrity of transformers – to make them better equipped to deal with the greater stresses that will affect future networks.

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