



# High-voltage bushings

100 years of technical advancement

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Reliability has always been one of the core demands of the energy market. One such example of reliability can be seen in the exceptional lifetime of power transformers, which often function for 50 years or more. This core demand is also fundamental for high-voltage bushings – critical components of all electrical networks, as their chief role is to prevent flashovers to ground.

Although many in the electric utility industry still regard the bushing as nothing more than a hollow piece of porcelain housing a conductor, the task it performs is quite extraordinary, involving advanced technologies in manufacturing and design with a lifetime exceeding the requirements of its applications.

Sophisticated calculation and design tools, improved material and production technology, and broad expertise are a result of over 100 years of experience in bushings, developed and manufactured at ABB in Sweden. As the world's largest supplier of bushings, ABB's flagship plant in Ludvika, Sweden, is equipped with state-of-the-art production lines that meet the increased demands associated with increasing voltage levels and reliability needs.

## PERPETUAL PIONEERING

A bushing serves to insulate conductors that are carrying high-voltage current through a grounded enclosure. To safely accomplish such a task without a flash-over is a challenge, as the dimensions of the bushing are very small compared with the dimensions of the equipment it is connecting. Controlling the stress (ie, electrical voltage, thermal current and mechanical stress) to get the dimensions right is of utmost importance in terms of bushing performance in the field during its lifetime.

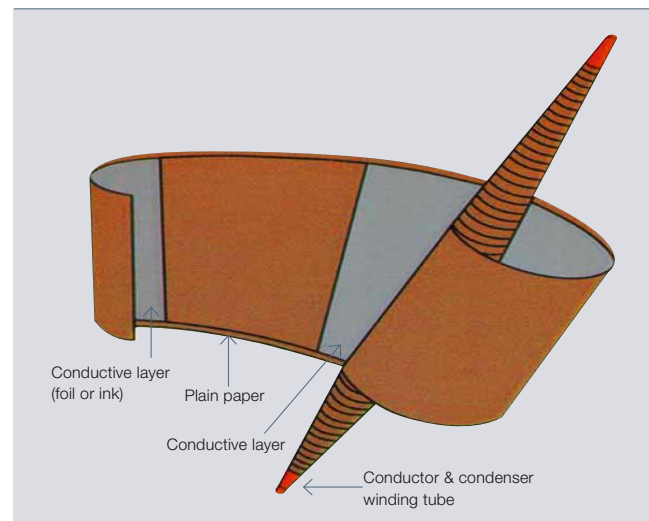
### High-voltage condenser bushings

Condenser bushings facilitate electric stress control through the insertion of cylindrically applied floating equalizer screens made of aluminum. The condenser core in which the screens are located decreases the field gradient and distributes the field along the length of the insulator, distributing it radially and axially in the condenser core **1**. The screens are located coaxially, to ensure the optimal balance between external flashover and internal puncture strength (ie, the electrical withstand of the condenser core).

At the start of the 20<sup>th</sup> century, bushings were dry insulated, made of Bakelite (resin-coated) paper and aluminum foil, with a flange glued to the condenser core and an insulator made of porcelain.

For years, condenser bushings have maintained the same basic design. Special paper envelopes the conductor, with metallic electrodes strategically placed inside the wrapping. These control the electric field of the bushing. The cylinder is impregnated with transformer-grade mineral oil or epoxy resin to further increase the electrical withstand, beyond that possible with only dry paper. The bushing is

**1** Schematic view of condenser core



therefore an enclosed apparatus fully separated from its application environment.

Oil-impregnated paper (OIP) and resin-impregnated paper (RIP) are the two main technologies in high-voltage condenser bushings. RIP technology is making a valuable contribution to better overall performance figures. The somewhat differently designed condenser core is vacuum impregnated by a curable epoxy resin to form a solid unit, free from oil **2**.

Both systems are designed and manufactured for long

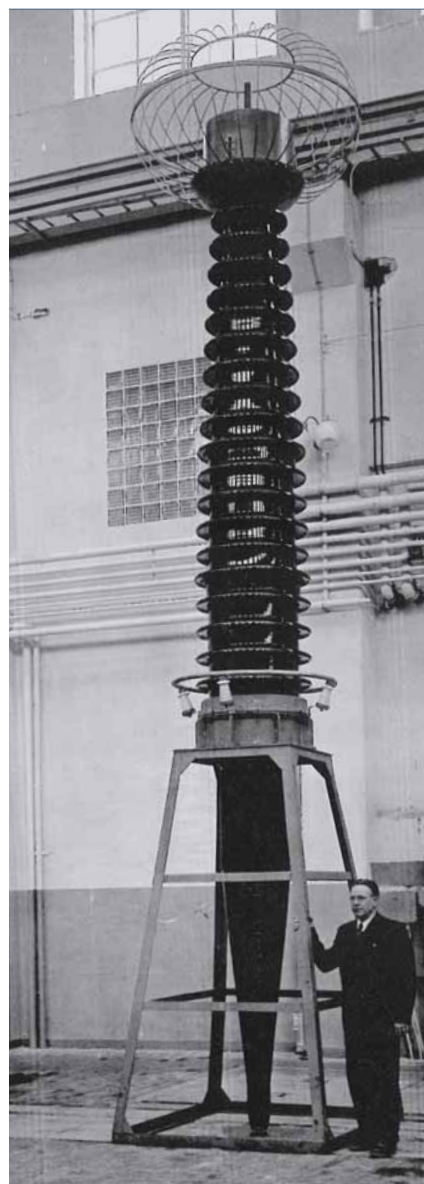
lifetimes and trouble-free performance, ensuring low partial discharge readings at well above the nominal voltage and ample margins for thermal runaways and overheating.

The outer insulation can be either ceramic or polymeric. Ceramic insulators have a long history and will be used for many years to come. However, it is likely that their role will diminish in the foreseeable future as the industry seeks improved insulator performance in order to reduce overall costs and improve safety, seismic withstand and pollution performance, as well as reduce insulator weights.

Controlling the electrical voltage, thermal current and mechanical stress to get the bushing dimensions right is of utmost importance.

To meet as many requirements as possible, bushings are configurable and are produced for system voltages up to 1,100 kV AC and 800 kV DC – even higher for test purposes. The largest bushing developed and manufactured at the Ludvika plant is an 1,800 kV AC transformer bushing with a length of 15 m. The limitation for the plant is not the voltage levels or bushing sizes, but rather the market need, where 1,100 kV AC and 800 kV DC are the highest voltages used today.

400 kV AC bushing from the 1950s



## PERPETUAL PIONEERING

### Historical review of bushings

At the start of the 20<sup>th</sup> century, bushings were dry insulated, made of Bakelite (resin-coated) paper and aluminum foil, with a flange glued to the condenser core and an insulator made of porcelain. These were suitable for voltages up to 190 kV.

Voltages increased to 220 kV in the 1930s and the conductive layers were changed to graphite. The graphite (ie, the semiconductive layer) concept is still used today by some manufacturers. The space between the condenser core and outer insulation is filled with oil and is open to the transformer.

In the 1960s, oil-impregnated bushings became the predominant technology – even today they have a market share of more than 80 percent.

In the 1940s, voltages rose to 400 kV, and condenser cores impregnated with oil and placed inside an insulating envelope of oil and porcelain were introduced.

But the early bushings had a high partial discharge and dissipation factor (tan  $\delta$ ), which increased with rising

system voltage. While sufficient for lower voltages, they left little margin for increasing applications. As voltages rose to 765 kV in the early '60s, this old technology was replaced with OIP systems. ABB thus supplied the first 705 kV bushings to Hydro Quebec in Canada.

At that time, oil-impregnated bushings became the predominant technology (this is still true today with a present market share of more than 80 percent). OIP bushings continued to be developed and resin-bounded bushing production was discontinued. Dry bushings, often referred to as RIP bushings, were introduced and have a growing market share.

In the 1970s, development of HVDC bushings for 600 kV began, and test installations requiring bushings for 1,800 kV AC were also underway. Even though both systems were oil insulated, they were significantly different in design.

RIP bushing development, which began in the '60s at ABB's Swiss sister plant, resulted in the production of 420 kV bushings in 1989 and 525 kV bushings in 1996. The reintroduction of dry technology is the direct result of powerful modern calculation tools as well as progress in material and production technology.

Recent (2006) HVDC transformer and wall bushings for 800 kV DC were developed and verified through extensive short- and long-term testing. The material properties change with time under DC stress and therefore long-term testing enables verification of the DC design before putting a new product into service. Based on experience in design, production processes and the latest achievements in calculation tools development, complex mechanisms such as ion migration and time-dependent charge distributions have been taken into consideration. The next step may well be 1,000 kV DC as a logical continuation of the achieved knowledge during the development of the 800 kV DC bushings.

Bushings are configurable and are produced for system voltages up to 1,100 kV AC and 800 kV DC.

In 2007, ABB designed and delivered AC bushings for up to 1,100 kV to China, and the long-established level for AC networks was increased from 800 kV to 1,000 kV AC <sup>3</sup>. This design relied on the knowledge from the 1,800 kV designs of the 1970s.

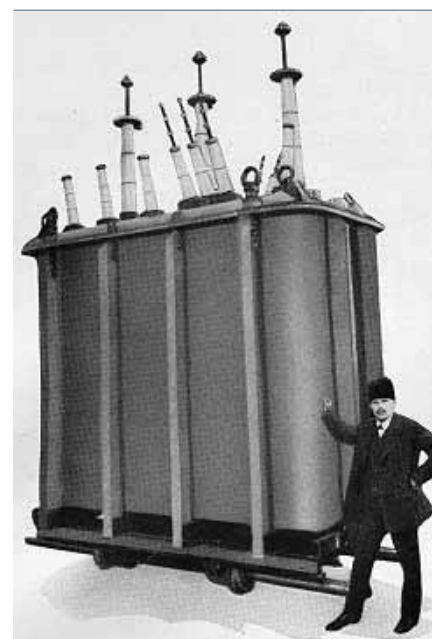
**2** Impregnation of RIP bushings



**3** Installation of 1,100 kV AC bushing (2008)



Transformer from the early part of last century



## PERPETUAL PIONEERING

Developing bushings for increasingly higher voltages and complex applications requires a great amount of experience and knowledge, as well as testing facilities far above the rated voltages – all of which are available at ABB today.

#### Technical challenges

Inherent in such complex devices are of course technical challenges. The highest voltage for equipment is generally limited by physical dimensions (ie, longer distances have higher electrical withstand). Also at high voltage levels another complication arises – namely the dielectric heating of the insulation. While the dielectric losses in a properly processed bushing can be neglected at low voltages, they become substantial at high voltage levels.

Insulation material has its lowest dissipation factor at approximately 60 °C and then increases with temperature. The heat has to be dissipated through the insulation and bushing surface. Thus, for each bushing, a limit exists that if exceeded will result in insufficient heat dissipation and consequently an uncontrolled temperature increase. This phenomenon, known as a thermal runaway, will eventually result in a breakdown.

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The dissipation limit is called thermal stability. Bushings naturally require full thermal stability at their highest voltage level while considering both the ohmic losses originating from the load current as well as the capacitive losses described earlier. The maximum allowed currents for a specific bushing and the dielectric losses coming from the voltage must therefore be judged both together and separately. For a properly designed bushing, the

dielectric losses and the rated current are not critical, and low-loss requirements do not contribute to the service life.

RIP technology represents a much larger challenge than OIP technology. This is because oil impregnation under vacuum is a relatively straightforward and forgiving process in the sense that oil fills out all parts of the bushing and remains in a liquid phase throughout its entire life. Void-free

products must be developed and manufactured with special attention, using the latest design tools.

To fully simulate the very specific manufacturing process, where exothermic reaction, thermo-chemical shrinkage and air circulations take place, it is necessary to include relevant mathematical equations in the theoretical models. Simulation-based modeling provides for cause-and-effect analysis, without which imperfec-

Konti Skan II transformer fitted with Ludvika bushings. Konti Skan is the HVDC transmission line between Denmark and Sweden.



800 kV DC converter transformer (2008)



## PERPETUAL PIONEERING

New UHV test facility (2009)



tions such as incorrect curing propagation, high temperature gradients, local overheating, high strain and stress (cracks), and shrinkage can occur. Besides numerical simulations of the manufacturing process, significant attention is placed on proper material selection, tailoring RIP materials for manufacturing optimization while taking into account field performance.

**ABB is at the cutting edge in optimizing processes to reach ever higher degrees of reliability and quality.**

Both OIP and RIP bushings are complex products, which, compared with the products available on a global scale, require high investments in equipment as well as research and development. The complexity rises heavily with increased voltages and currents. But these challenges push ABB to create optimized, state-of-the-art bushings for its customers.

#### Quality assurance

Bushing production processes have seen decades of continual development resulting in extremely high yields. This does not, of course, mean that the end of the road has been reached.

ABB is at the cutting edge in optimizing processes to reach ever higher degrees of reliability and quality. This is evident in the most critical manufacturing steps, for example in the winding of the condenser cores where state-of-the-art machines control the winding and equalizer screen insertion, or during drying and impregnation where the process is controlled and monitored by computers and highly experienced teams working with machines.

Another area that has seen excellent advancement over the years is statistic process control and the automatic checking of process limit values with the implementation of new technology.

A global reporting network is in place, requiring all ABB units to report all

major events within 24 hours. This provides a good base for event classifications. Cross-functional meetings are held to review and prioritize this information and implement the subsequent corrective or preventive actions in design and production.

ABB's role in bushing production and development is strong, with sites in Brazil, China, India, Russia, South Africa, Switzerland, the United States, and particularly Sweden.

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#### Further reading

**Holaus, W., Stucki, F.** Breaking news: Ultra-high-voltage switchgear to power China. *ABB Review* 4/2008, 20–24.

**Heinemann, L., Besold, F.** Compact and reliable: Decades of benefits – Gas-insulated switchgear from 52 to 1,100 kV. *ABB Review* 1/2009, 92–98.