Pluggable bushings up to 550 kV are quick and easy to install, requiring no oil work – time requirements are reduced by up to 75 percent when transformers are first installed.

Pluggable bushings: More flexibility for existing and new grid facilities

ABSTRACT
Pluggable bushings offer numerous advantages over conventional bushings, but with the same performance characteristics: simple and much faster to install, they do not require any oil or gas work on site in the substation; they are solid-insulated, explosion-proof, and can be replaced and used over again at any time. Plus they are significantly shorter, requiring considerably less space inside a transformer. Of course, the same is true for use in gas-insulated switchgear (GIS). Demand for pluggable bushings, which were developed around twenty years ago mainly for testing and measurement purposes, has been steadily growing in recent years – together with their scope of applications. Given the changing grid structure and rising challenges associated with the energy transition, grid operators worldwide recognise the advantages of pluggable bushings in terms of greater planning flexibility and the future flexible use of transformers.

KEYWORDS
pluggable bushings, flexible transformers, future-proof grid structure

1. Introduction
In the years ahead, increasing decentralisation of power generation will require continuous adjustments to the grid structure. Transformers need to be quick to install, interchangeable, and permit a variety of uses in the long term. Meanwhile, increasing urbanisation is placing increasing demands on existing substations. Within space constraints and with interruptions kept to a minimum, they need to be modified for higher capacities. Connection components such as bushings play a key role. For example, pluggable bushings enable rapid installation of equipment for temporarily bypassing a transformer, or for its permanent operation – both for
Pluggable bushings also enable reconfiguration of the grid structure, and due to increasing decentralisation of power generation, this need will increase in the years ahead.

3. Challenge: Combining capacitive with geometric control

With pluggable cable connectors, terminations, surge arresters and bushings, a comprehensive product portfolio is available for pluggable connection systems from 6 kV to 350 kV. There is one crucial feature in the development of pluggable bushings, however: while pluggable cable connectors join together geometric field controls on each side, a pluggable bushing has to combine the socket's geometric control with the capacitive bushing. The compact design offering the advantages both of the pluggable bushing and the space-saving, standardised connector in the transformer is possible only by combining the two field control types.

The composition of pluggable bushings is illustrated here using the example of an HV-CONNEX Gr 7-S bushing for voltages up to 362 kV. Numerous product variants of different sizes for voltage levels from 125 kV to 362 kV are now available—and a pluggable bushing for up to 550 kV is currently in development.

4. High current-carrying capacity up to 2,600 amps

The actual conductor is located inside the bushing. Fig. 2. Usually it is made of copper, though aluminium is possible in some cases. To counteract the strong warming of the conductor and hence the danger of overheating, which is amplified by the insulation, the bushing uses “heat pipe” technology: the conductor consists of a copper tube containing a liquid which sublimates into a gaseous state as the temperature rises. The hot gas circulates inside the conductor and condenses, thus continually transporting the heat/energy upwards. This type of cooling is also found in other technical applications, such as for processor cooling in supercomputers—but on a far smaller scale. Using heat pipe technology in the pluggable bushing enables maximum currents up to 2,600 amps in a minimum of space.
Copper-beryllium lamellas on the contact part of the bushing, Fig. 3, no. 4, ensure optimal contact for the plug connection, even under different ambient temperatures in summer and winter. Making electrical contacts by means of contact lamellas is based on the line contact principle, offering higher current-carrying capacities compared to planar contacts. At first sight, a planar contact surface seems an ideal contact point: two smooth surfaces lie flat on one another, electrical energy can flow over the entire overlapping surface. Under the microscope the visual appearance turns out deceptive. A rugged landscape is revealed, full of peaks and valleys. These irregularities in the surface of the material, which are called surface roughness, have consequences for the contact quality. As a result of numerous measurements, a hundred percent contact area effectively shrinks to a few metallic and thus electrical contact points, which leads to only five percent of the total overlap surface. This argument lead to a paradigm change in contact technology: the removal of large contact surfaces towards smaller but defined contact points with high contact pressure.

5. RIP or RIS insulation

Various options are available for the insulation of the conductor, Fig. 2, which is the central core of the bushing. As with conventional bushings, Resin Impregnated Paper (RIP) or Resin Impregnated Synthetics (RIS) insulation is commonly used; these consist of paper or synthetic fabric impregnated with epoxy resin under vacuum. The insulation is wrapped around the central conductor in the bushing. Both materials – RIP and RIS – are available for pluggable bushings. Because paper is very dense, however, it only permits the use of high purity, very low viscosity epoxy resin. By contrast, RIS insulation is more permeable, so fillers can be used, e.g. to enhance thermal conductivity.

6. Electrical field control: Capacitive and geometric

The electrical field in the bushing is controlled capacitively. When the bushing is manufactured, conductive foils are applied to the conductor alternately with the RIP or the paper-free synthetic fabric RIS insulation, similar to conventional foil capacitors. This arrangement generates a series circuit of capacitances. The individual foils are not at any defined potential. Only the first and last foil are connected to the high-voltage and earth potential. Fig. 4, to achieve a high degree of homogeneity. The same voltage drops across each of these capacitors and forms a homogeneous field in the insulating material. The length, spacing and number of foils are chosen accordingly to generate the desired integrated capacitances. In Figures 5 and 6, the capacitive field control is pictured primary as a scheme and secondary as a field density plot. The lines are showing the equipoten-
A paradigm change in contact technology was deployed: the removal of large contact surfaces towards smaller but defined contact points with high contact pressure.

The crucial innovation consists in combining the bushing’s capacitive control with the socket’s geometric control. With conventional bushings, capacitive control continues directly in the transformer or GIS, compare also Fig. 3 on the right side – with the result that the system-side end of the bushing inside the transformer is significantly longer. When operated with a cable plugged in, the cable connector and the socket in the transformer are both controlled geometrically, not capacitively. In this case, the homogenisation of the field is achieved via the shape of the electrodes, which means that the end of the screen, black part in Figure 7, has to be modified in such a way as to produce an optimal field distribution, Figs. 7 and 8. It can be seen in both pictures that the distances between the equipotential lines are as good as constant, which is desired for the field control.

Although geometric control is thicker in diameter, it is substantially shorter. When a capacitive bushing is used together with a geometrically controlled socket, both types of control have to be matched to each other. It is important that the field exposure limit is not exceeded, both in the insulation of the two individual components and in all adjoining insulating media. Combining both control types in the pluggable bushing and the socket has succeeded in enabling maximum power in a minimum of space, compare also Fig 3.

7. Reduced installation depth enables new generation of grid facilities

The combination of capacitive and geometric field control in pluggable bushings

Figure 2. Composition of a pluggable HV-CONNEX Gr. 7-S bushing up to 362 kV. Heat pipe technology for cooling the conductor enables maximum currents in a minimum of space

Figure 3. Contact and flange region of a pluggable bushing

The crucial innovation consists in combining the bushing’s capacitive control with the socket’s geometric control of electric field

Figure 4. Structure of capacitive control and layers
reduces the installation depth in the transformer or GIS by about a third compared to a conventional bushing. Fig. 9. This allows significantly more compact designs for new grid facilities, and more flexible applications. Based on the pluggable HV-CONNEX Gr. 7-S bushing and the pluggable CONNEX socket, Siemens have developed compactly designed resilience transformers that are easy to transport by lorry, can be moved within a few days, and are operational within a few hours. This was made possible because the socket, thanks to its short length, could be built into the top of the transformer, thereby saving space, and because the pluggable bushing guarantees rapid assembly. Other compact systems and installations are conceivable.

8. Special feature regarding the positioning of current transformers

Although the shorter installation length of the pluggable socket is clearly an advantage, it also means that a change is necessary with regard to the positioning of current transformers. Because the contact element and socket are geometrically controlled, a current transformer cannot be positioned directly at the bushing connection in the transformer, as was previously usual. While this is easily possible in the case of a conventional bushing with capacitive control, owing to the field control resulting from the foils, the shorter geometrically controlled socket does not offer any field-free space outside the socket connection that is suitable for placing a current transformer around the conductor. This would only be possible by enlarging the current transformer, but this is cost-intensive. An advanced idea is to integrate the current transformer into the socket or bushing itself, so that both form an enclosed unit. This solution would not only be the most compact, but also the most economical connection option for the transformer. Consequently, it represents the next innovation step in pluggable connection technology.

9. Maximum mechanical stability

To achieve high mechanical stability, the bushing’s RIP or RIS insulation core is surrounded by a silicone-shielded glass-fibre reinforced plastic (GFRP) tube, Fig. 2. The gap between the insulation core and tube is then filled with an insulating polyurethane foam to further increase the dielectric strength on the exposed side. The GFRP tube also forms a diffusion barrier and protects the insulation core.
against moisture absorption. The shields applied to the outside of the GFRP tube serve to lengthen the creepage distance and prevent leakage currents on the bushing’s exposed side. Silicone is ideally suited to this purpose owing to its good ageing resistance and lower adhesion of dust and contaminants (self-cleaning effect, hydrophobic) [2].

The flange region, Fig. 3, no. 2, in the connection to the bushing connects the bushing to the pluggable contact part. Test taps integrated into the side of the flange provide measurement and control capabilities, and are always available in a version conforming to the IEC standard [3] up to 2 kV dielectric strength, and also for the U.S. market up to 20 kV in accordance with the ANSI standard [4], [5]. The test connections are used to measure the loss factor (tan δ) or partial discharges, and hence to detect ageing-related damage to the bushing, e.g. as a result of moisture ingress. However, since the pluggable connection between bushing and socket seals hermetically, moisture ingress is impossible.

Both the contact part of the bushing and the socket, which is installed in the transformer, are solid-insulated. The connection between the bushing and socket is critical for the faultless dielectric function. It is important to ensure that the contact pressure between the components always has a defined value, and that a homogeneous pressure pattern is formed. The solution consists of a silicone insulator for the expansion gap, which is firmly bonded onto the surface of the insulation core. To absorb the differences in expansion between the two components when the conductor heats up, a special spring mechanism provides constantly high and uniform contact pressure, thereby ensuring electrical insulation within the plug connection. Numerous digital simulations and prototypes were produced in the early development stages to find the optimal electrical dimensioning of the insulation core and silicone element.

Conclusion
As the successful use of pluggable bushings for two decades shows, the mechanical, electrical and manufacturing challenges of interfacing capacitive with geometric control in the socket have been mastered. Pluggable bushings thus offer many advantages over conventional bushings in respect of handling and installation, installation length, and the future viability of the technical installation as a whole. Since they are oil-free, gas-free and solid-insulated, they are also maintenance-free, explosion-proof, and readily storable without oil. The bushings are 100 percent factory pre-tested, and can be fitted and put into service immediately at the site of operation. Thanks to their dry pluggable connection capability, installation is easier and considerably quicker - the installation time for bushings is reduced by up to 75 percent when a transformer is first installed. On-site oil and gas works are completely eliminated. Replacing the connection components is just as easy: If a connection from an overhead power line to an underground cable is desired, the bushing can simply be unplugged, and the equipment connected to the underground cable using a suitable cable connector. The socket stays in the equipment and the pluggable bushings can be reused at any future point in time. In principle, the universal socket offers maximum flexibility for the future use and reconfiguration of grid facilities. Today, the proven product range covers the complete voltage range from 123 kV to 362 kV – and will soon extend up to 550 kV. Thus a few variants of the pluggable bushing are sufficient for the entire application spectrum, since different voltage levels can always be implemented within one component family.

Figure 9. Length comparison showing a conventional bushing alongside a pluggable bushing. With the pluggable bushing, the installation depth in the transformer is reduced by about a third. (Example for 245 kV, pluggable system 470 mm inside transformer, conventional 620 mm [1]).
Table 1. Specifications for HV-CONNEX size 7/7-S at a glance [4]

<table>
<thead>
<tr>
<th>HV-CONNEX Bushing</th>
<th>Size 7 [RIS]</th>
<th>Size 7 [RIP]</th>
<th>Size 7-S [RIS]</th>
<th>Size 7-S [RIP]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage $U_{L}$</td>
<td>up to 145 kV</td>
<td>up to 265 kV</td>
<td>up to 362 kV</td>
<td>up to 362 kV</td>
</tr>
<tr>
<td>Art.-No.</td>
<td>828 193 005</td>
<td>828 193 002</td>
<td>828 193 004</td>
<td>828 193 003</td>
</tr>
<tr>
<td>Applicable standards</td>
<td>IEC 60137:2008 / IEEE C57.19.00-2004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>2370 mm</td>
<td>3444 mm</td>
<td>4280 mm</td>
<td>4280 mm</td>
</tr>
</tbody>
</table>

**Environment Conditions**
- Max. Installation altitude: 1000 m MSL
- Environment temperature: from -25 to +50 °C

**Installation Conditions**
- Pollution Class acc. to IEC 60815 Class IV: 31 mm/kV
- Flash over distance: 1330 mm / 2434 mm / 3250 mm / 3250 mm
- Max. operating load: 2500 N
- Mounting position: vertical, e-/- 30°

**Electrical levels**
- Rated frequency: 50-60 Hz
- Highest voltage [IEC/IEEE]: 145 / 138 kV / 245 / 230 kV / 342 / 345 kV / 342 / 345 kV
- Voltage tap: 2 kV
- IEEE Voltage tap: 20 kV
- Max. current rating: up to 2600 A / up to 2600 A / up to 2000 A / up to 2000 A

**Stress control**
- Field control method: capacitive/geometrical, capacitive, capacitive, capacitive
- Type: RIS technology, RIP technology, RIS technology, RIP technology

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**References**

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6. P.K. GmbH, *Datasheet HV-CONNEX pluggable Bushing size 7-S up to 362 kV*

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