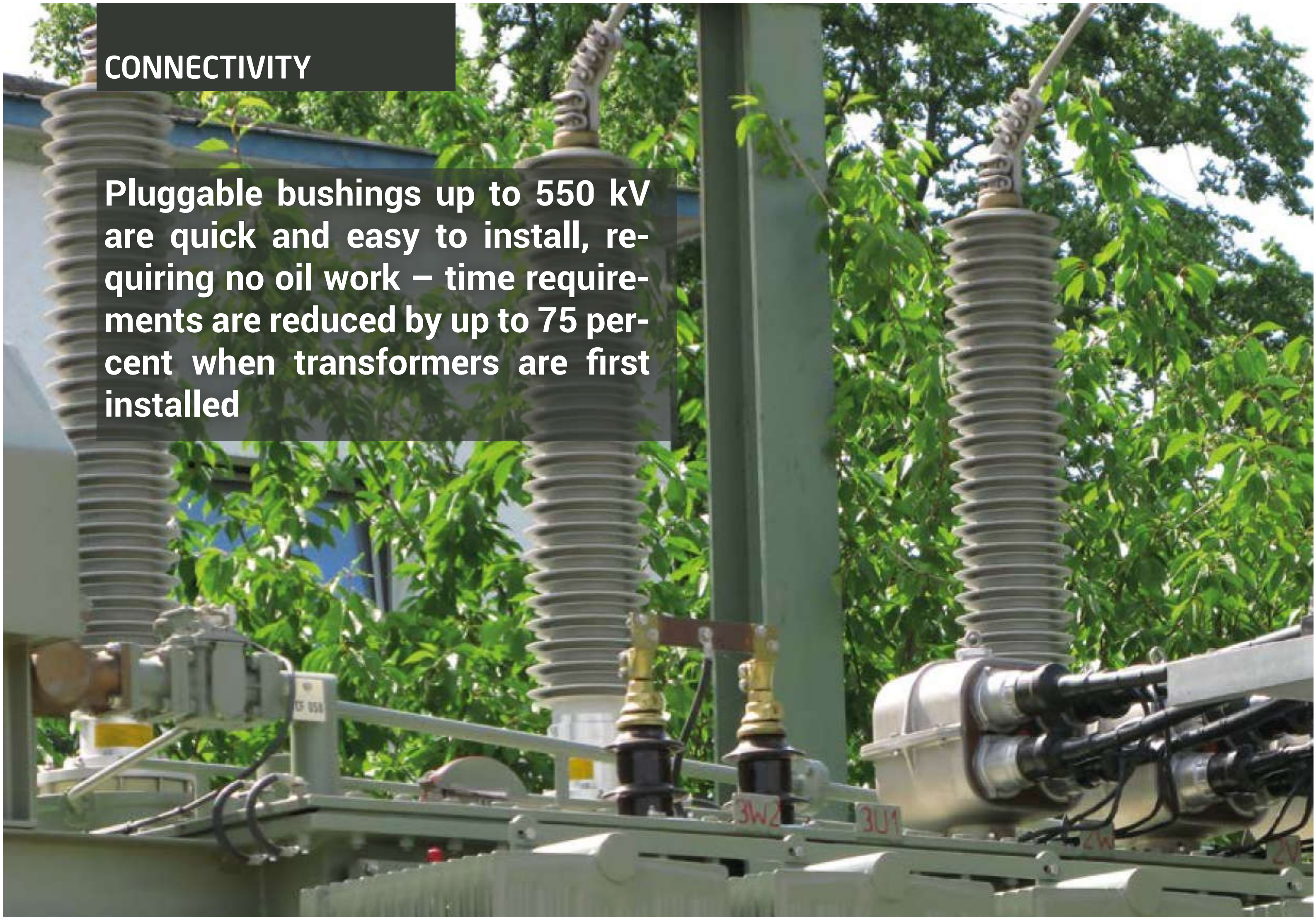

Pluggable bushings up to 550 kV are quick and easy to install, requiring no oil work – time requirements are reduced by up to 75 percent when transformers are first installed

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

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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

new installations and for modifications to gas-insulated or conventional switchgear. What is more, the ability to simply replace the pluggable components increases the reliability of the overall system. The outage times during maintenance or during midlife refurbishment are reduced significantly, meaning that the redundancy within the substation is restored in less time. With the standard design, the midlife refurbishment requires a substantial amount of work. The oil-filled transformer is disconnected from the grid, the oil level lowered, the bushing replaced and subsequently the entire connection technology reconnected. It may sometimes be necessary afterwards to draw a new vacuum under oil. This leads to a three-day downtime to allow any air bubbles formed during the procedure to escape. The procedure is much simpler and, as such, much cheaper with a transformer equipped with a universally pluggable interface. After switching off, the old bushing is simply unplugged and the new one plugged in. This only takes 1.5 hours to complete, after which the grid operator can restore the redundancy within the substation. For the Total Cost of Ownership (TCO) calculation, this means minimal costs for personnel and system downtime.

Apart from easy installation when building new facilities, during replacement, and for flexible reconfiguration of stationary systems, pluggable bushings are also advantageous in temporary applications. Thanks to their solid insulation, there is absolutely no environmental risk when temporarily replacing overhead power lines with cables. Moreover, they simplify and speed up the construction of temporary systems.

2. One interface – many connection possibilities

The basic requirement for being able to use pluggable bushings is to have a universal pluggable interface in the transformer. This offers far more flexible application options than conventional, fixed connection systems. For example, both bushings and cable connections can be used via the same socket, without having to intervene in the sensitive inner workings of the systems, Fig. 1. The dry, solid-insulated and pluggable socket is also more compact, so it takes up less space. As a result, transformer designs can be more compact. With regard to their future uses, transformers or GIS equipped with a pluggable interface are much more flexible and capable of operating for decades even under changing requirements. To ensure future expandability, it is even possible to close a socket using a voltage proof dummy plug, and then use it when needed as an additional pluggable connection. Changing from pluggable bushings to HV cables and vice versa is easily possible at any time.

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 550 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 123 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 circulation 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.

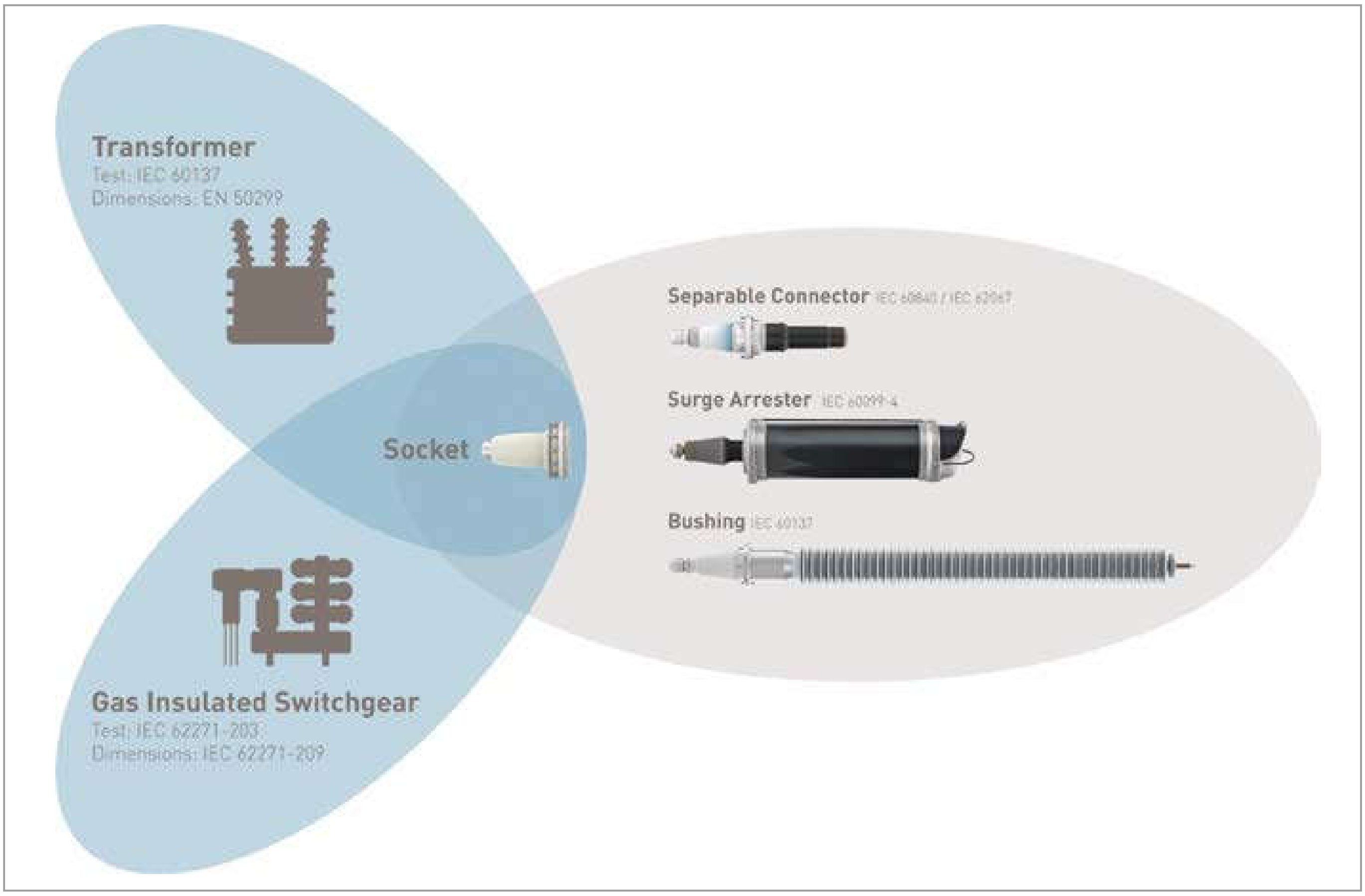

Figure 1. A universal pluggable socket makes it easy to change between bushings, cable connectors or surge arresters, without intervention in the system

Pluggable solutions are significantly shorter, requiring roughly one third less space inside a transformer, and enabling more compact transformer design

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

tial areas. As it can be seen, the distances between the lines are made homogenous due to the different length of the foils.

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

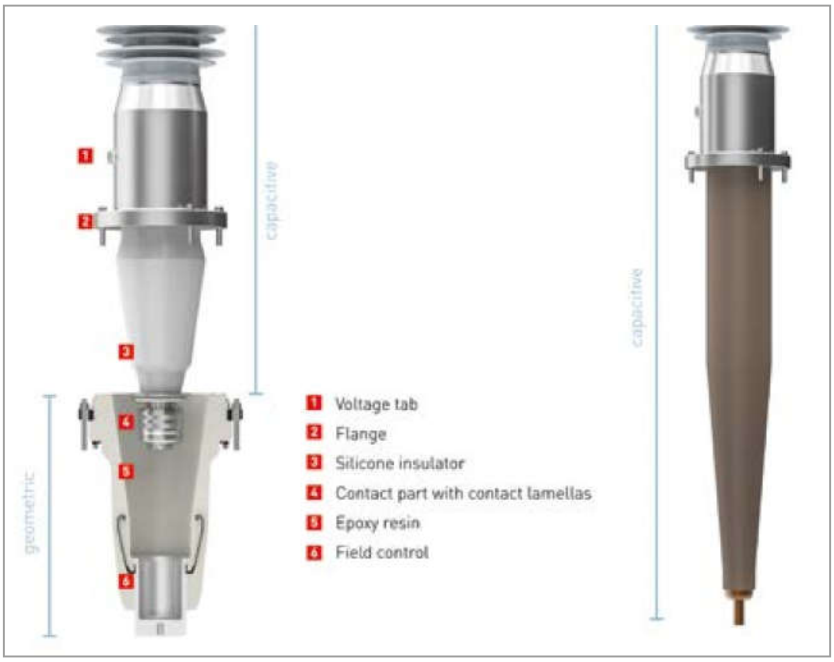

Figure 3. Contact and flange region of a pluggable bushing

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

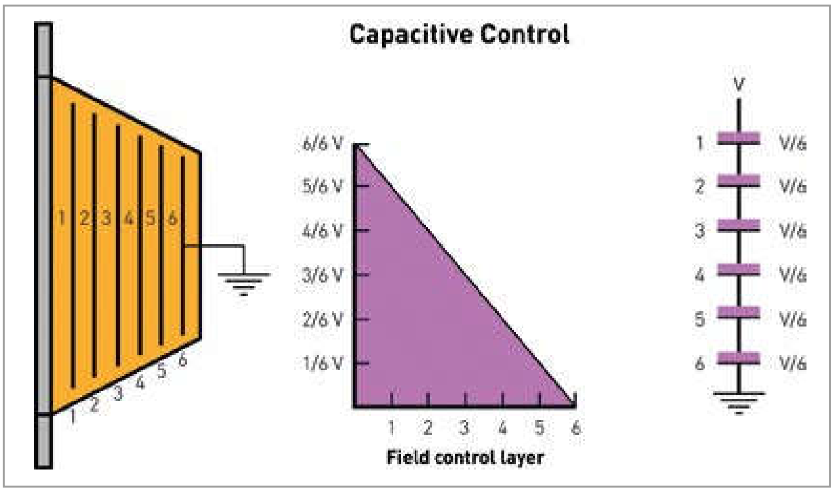

Figure 4. Structure of capacitive control and layers

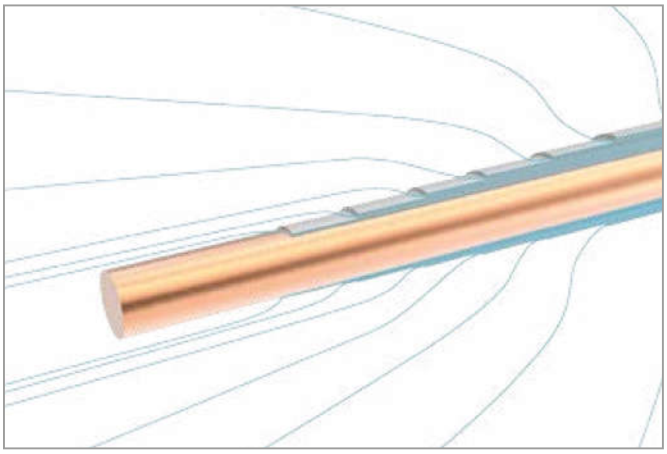

Figure 5. Capacitive control in the bushing at the upper and bottom ends of the foils

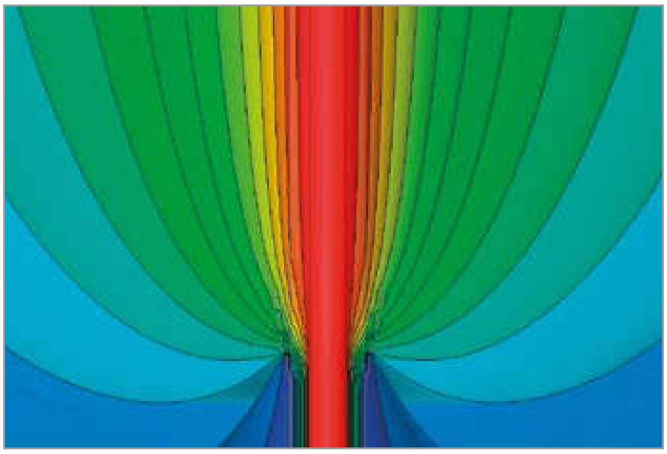

Figure 6. Electrical field simulation, capacitive control

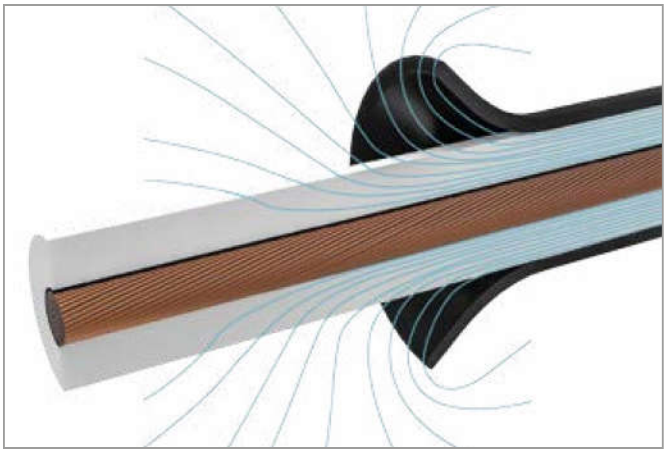

Figure 7. Geometric control which can be found inside the pluggable connection area in the connector and the socket

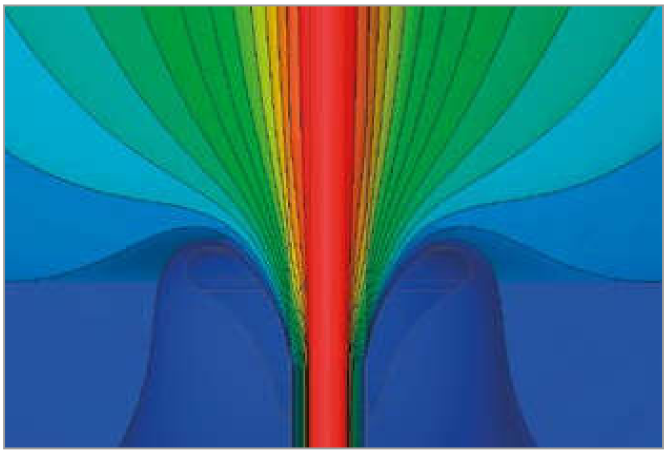

Figure 8. Electrical field simulation, geometric control

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.

Current transformers integrating into the socket or bushing itself was another advanced idea deployed here

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]

HV-CONNEX Bushing	Size 7 (RIS)	Size 7 (RIP)	Size 7-S (RIS)	Size 7-S (RIP)
Voltage U_m	up to 145 kV	up to 245 kV	up to 362 KV	up to 362 kV
Art.-No.	828 193 005	828 193 002	828 193 004	828 193 003
Applicable standards	IEC 60137:2008 / IEEE C57.19.00-2004			
Length	2370 mm	3464 mm	4280 mm	4280 mm
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, +/- 30°			
Electrical levels				
Rated frequency	50-60 Hz			
Rated voltage	132-138 kV	220-230 kV	330-345 kV	330-345 kV
Highest voltage (IEC/IEEE)	145 / 138 kV	245 / 230 kV	362 / 345 kV	362 / 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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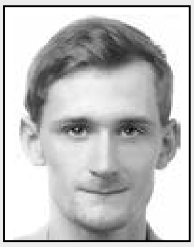

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