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A3 Transmission & Distribution
PS2 Decarbonization of T&D Equipment
>SF6 Alternatives for MV and HV application

Pressurized air insulated cables: A novel, compact GIL design for 12 kV- 420 kV: Design, Simulation, and Test results

Dr. Walter Holaus[1]; Prof. Dr. Michael Schueller[2], Matthias Schneider[2],

[1]Hivoduct AG; [2]Eastern Switzerland University of Applied Sciences OST, Switzerland

walter.holaus@hivoduct.com

SUMMARY

To replace SF_6 gas in Gas-Insulated Lines (GIL) and in busducts for Gas-Insulated-Switchgear (GIS), and to avoid complications with a variety of alternative gas mixtures, a new generation of pressurized air cables which use dry air for insulation were developed.

Pressurized air requires larger insulation gaps and higher operating pressure which both are enabled by a new mechanical bus and flange design which provides better dielectric shape, less manufacturing steps, does not require welding and builds very compact by not using flange bolts.

The electrical design for pressurized air insulated cables (PAC) and resulting optimization using the new flange design is presented in detail in this paper. With the proposed design, SF_6-free air-insulated cables are similar size like existing GIL using SF_6 or other insulation gas mixtures.

Bursting pressure tests results according SVTI 704 confirm mechanical integrity up to 50 bar. Dielectric tests for AC and BIL up to 650 kV_p have been conducted and match the proposed dimensioning guideline. A thermal time constant of ~2h was measured during temperature rise tests on 145 kV PAC – showing an enclosure temperature of <41°C at 1500 A for > 10h.

To reduce space requirements for installations, a triangular arrangement of three phase systems together with a roller design was developed, which allows installation into – and removal from – confined spaces such as pipes and microtunnels.

It is concluded that pressurized air insulated cables are a viable, type tested, SF_6-free option for medium- and high-voltage electric energy transmission – which can replace Gas Insulated Busducts GIB or Gas Insulated Lines GIL, HV lines, and HV cables with reduced environmental impact and improved technical characteristics.

KEYWORDS

Gas insulated lines – Gas insulated busducts – Pressurized Air Cable – Flange design – Cable – Busbar – GIL – GIB – High voltage – Medium Voltage – SF6 free

INTRODUCTION

Pressurized air insulated cables are based on a coaxial arrangement of a HV conductor inside a grounded, conducting enclosure – like gas-insulated lines (GIL). The basic properties of GIL as well as the product design and applications are well known [2], [3], [4]. GIL applications were enabled by the excellent dielectric strength of pure Sulphur hexafluoride (SF6) gas, SF6/N2 gas mixtures or, recently, also other SF6 free gas mixtures, resulting in compact dimensions when using a standard GIS flange design.

There are 3 main applications of GIL type products:

1. Busbars and exit busducts for GIS -> Using SF_6 gas or insulation gas mixtures
2. Replacement for HV lines and cables -> Enabling higher currents and less losses
3. Generator busducts -> Typically using air insulation at MV levels

Most of today's GIL applications are GIS busbars and GIS exit busducts – as these are extensions of GIS switchgear where the connection function is done with the same insulation technology. Applications to replace HV lines and HV cables had limited market success so far – although GIL have superior technical performance [2], [3], [4], [10].
The main reasons for this are:

a) Use of large quantities of SF_6: related risk of gas leakage and environmental concerns
b) Complex bolted flange design: High cost and risk of gas leakage over lifetime
c) Welded flange design: On-site welding of enclosures [5]
   - Welding & X-ray or ultrasonic testing ensures gas tightness over lifetime.
   - But disables non-destructive revision or disassembly
d) Limited flexibility of enclosure tubes for installation and temperature elongation

As SF_6 is the most potent among the greenhouse gases identified by the Intergovernmental Panel on Climate Change (IPCC), it meanwhile has been banned from most applications – except for gas-insulated electrical switchgear (GIS); because cost-effective and environmentally sound alternatives were unavailable when the EU F-Gas regulation [1] was last revised in 2014. An upcoming revision may further tighten any use of SF_6.

Meanwhile several alternative gases and gas mixtures are available for use in high-voltage applications and products [6], [7]. Besides the main goal of low GWP potential and being non-toxic, these gas mixtures have been designed to have **similar dielectric strength** than SF_6, see Fig. 1. This property allows re-use of existing design guidelines, product dimensions, materials, machinery, and factory infrastructure. Therefore, it simplifies transition to SF_6 free products for **established** manufacturers. However, if a ground-up new design is pursued with the aim of **a best fit to the chosen insulation gas** without this heritage, a one-to-one dielectric replacement of SF_6 gas is not required.

The proposed new design of pressurized air insulated cables has overcome the known GIL limitations by using a new design that fits to **pressurized air for insulation**, by using a **new bus and flange design** for quick and gas-tight assembly and by adding **flexible components**.

They are named "pressurized air insulated cables (PAC)" as this best describes the functionality without referring to a specific insulation gas as in GIS or GIB. Details on design, testing and applications are provided in this paper.

Selection of insulation gas: Pressurized air

A tremendous amount of research has been conducted in the past decades to search for viable alternative gases to SF_6 for high-voltage applications. An overview on SF_6 vs. alternative insulation gases for various technologies, applications, and voltage levels in provided in Fig. 1. taken from [6].

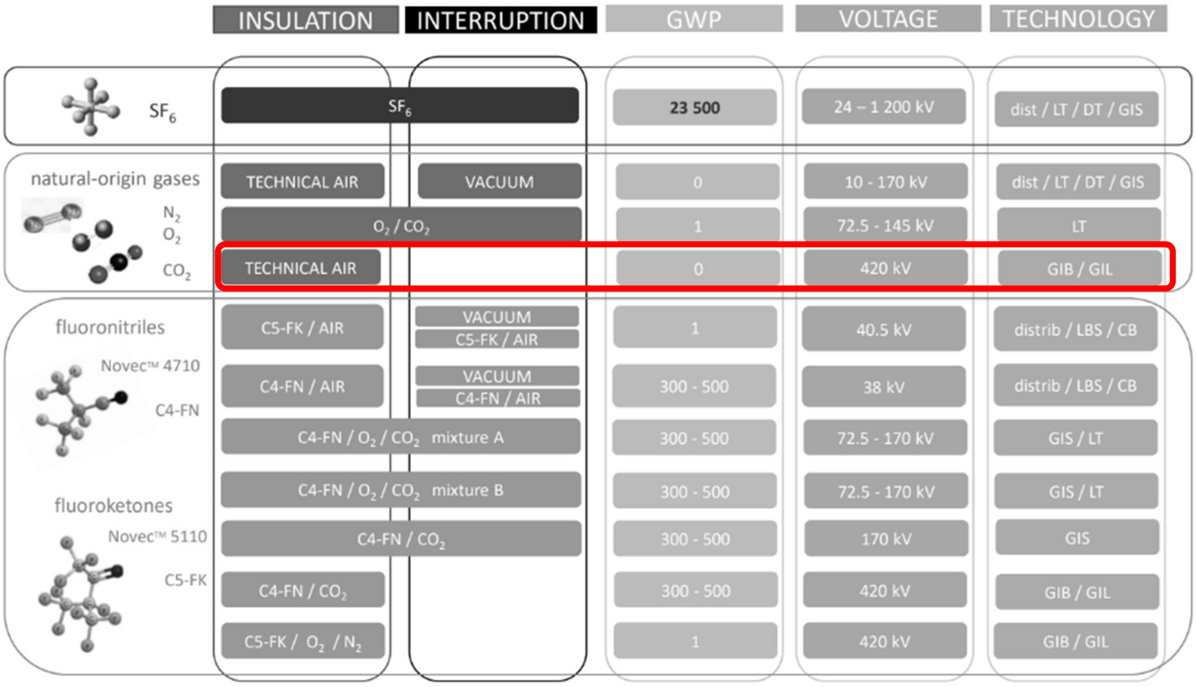


Fig. 1: SF_6 gas and alternatives: Application, GWP, voltage levels and technologies [6].

Air is the most common insulation gas used for air-insulated lines under outdoor conditions. **Technical air** (N2: 80%, O2: 20%, dry) has well-known and researched dielectric properties, is low cost, easy to handle, has zero GWP, is non-toxic and can be released to environment after use in a GIL.

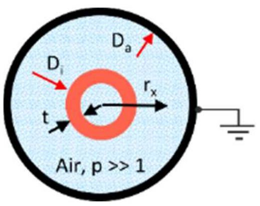
Therefore, **pressurized technical air has been chosen as insulation gas for pressurized air cables** – providing a dielectric breakdown strength for BIL dimensioning according to Eq.1:

$$E_{bd} = 24 \, \frac{kV}{cm \; bar} \cdot p^{0.92} \qquad \text{Eq. 1}$$

The pressure exponent 0.92 accounts for a non-linear increase of dielectric strength with pressure and limits the reasonable maximum air pressure to ~12 bar [10].

Basic dimensioning: Conductor and enclosure for pressurized air cables

In a coaxial single-phase arrangement of a high-voltage conductor centred in an enclosure, the electric field is highest at the conductor and decreases towards the outside acc. to Eq. 2:



$$E_{coax}(r_x) = \frac{U}{r_x \cdot ln\frac{D_a}{D_i}} \qquad \text{Eq. 2}$$

$$A_{Cond} = \frac{\pi}{4}\left(D_i^2 - (D_i - t)^2\right) \qquad \text{Eq. 3}$$

The optimal diameter ratio for dielectric design follows from Eq. 2 and is $D_a/D_i = e = 2.71$. However, considering the cross section of the conductor for continuous current capability acc. Eq. 3, and using the same conductors for different products, offsetting from the optimal ratio is reasonable from portfolio considerations – specifically for MV applications.

Fig. 2 shows how the max. coaxial field stress acc. to Eq. 2 changes for fixed outer diameter D_a and varying conductor diameters D_i for 3 different products.

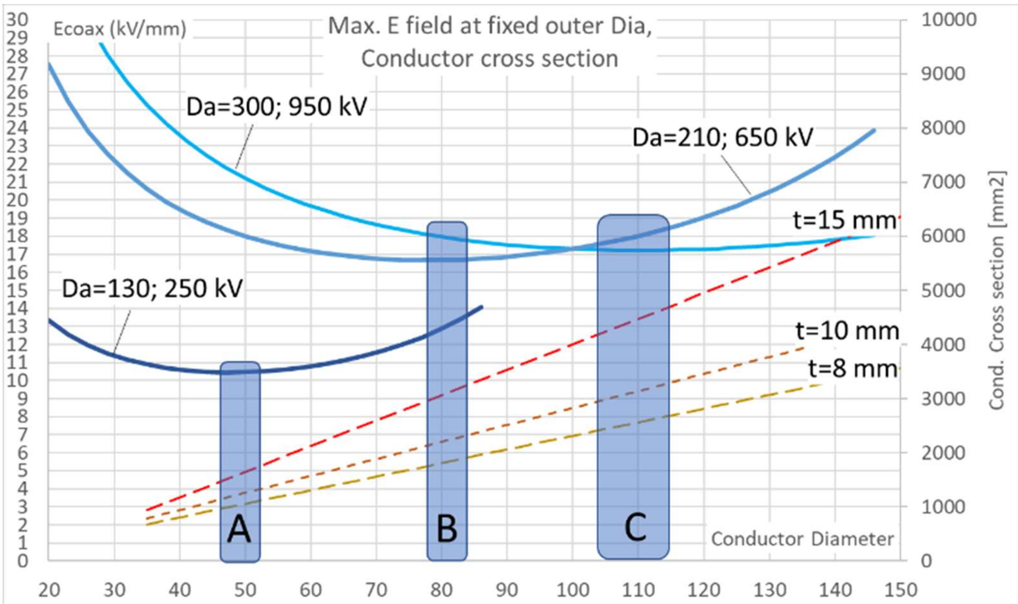


Fig. 2: Max. coaxial field stress for fixed Da and variable Di and conductor cross section.

For D_a= 130 mm, the optimum conductor diameter is D_i~50 mm, see region "A". The according conductor cross section is 1000-1600 mm^2 which is sufficient for rated currents up to ~1500 A. Same conductor dimensions may be used for different products, see e.g., region "B" and "C" which are close to the optimum for D_a ranging 200-350mm. A conductor thickness t >15 mm is not reasonable for AC applications due to skin depth being ~12 mm in aluminium @ 50Hz.

Note that the field stress E_{coax} is an analytical result for the coaxial arrangement only. In a detailed design with spacers, contacts and angles, the actual field stress must be derived by simulating the actual geometry and is always higher than E_{coax}.

Fig. 3 shows the result of a dielectric simulation on a detailed flange design for D_a= 130 mm and D_i=80 mm. It shows that the field stress is highest along the spacer shield (which is intended) at E_{max}=16.3 kV/mm and less in the triple points on each side of the spacer.

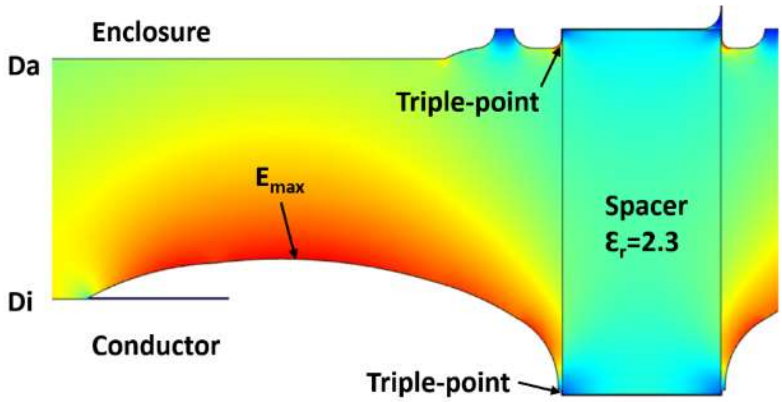


Fig. 3: Field stress results from simulating spacer and shield for D_a=130 mm and D_i=80 mm.

Therefore, E_{max} is ~25 % higher than E_{coax}, equalling a utilization factor of ~75 %. Using the breakdown strength of air acc. Eq.1 and the resulting field stress from actual design acc. to Fig. 3, the required air pressure inside the enclosure can be determined, see Tab. 1.

This basic dimensioning leads to the product dimensions and ratings acc. Tab. 1:

U_r kV	BIL kV_p	I_r A	D_a mm	D_i mm	E_{coax} kV/mm	E_{max} kV/mm	p_{min} bar, abs	C pF/m	R_{AC} µΩ/m
52	250	1500	130	50	10.5	13	6.8	58	27
52	250	2000	130	80	13	16.3	8.5	115	16
145	650	2000	210	80	16.8	20.8	11	58	16
123	550	4000	210	110	18	19	10.5	86	11
245	900*	2000	300	80	18	20.8	11	42	16
245	900*	4000	300	110	17	20.8	11	55	11
245	1050	4000	350	110	17	20.8	11	48	11

*The standard BIL test value for U_r=245 kV is 1050 kV. However, a reduced BIL test level may be specified, as PAC have grounded enclosures and are operated underground with surge arrestors on each end. Note: each product can be used for U_r lower than the maximum by reducing the inside air pressure accordingly. This provides a simple scaling option without a new enclosure design.

Flange design without bolts for pressurized air cables

The requirements for the new flange design for pressurized air cables are:

- Rated pressure of 11 bar, requiring bursting pressures > 32 bar [11]
- Gas tightness for pressurized air over lifetime
- No welding and no bolting required
- Applicable to flanges of various components (bus, angle, compensator, bushing, ...)

These requirements led to a new flange design as shown in Fig. 4 in comparison to a traditional GIS flange design and a welded flange design.

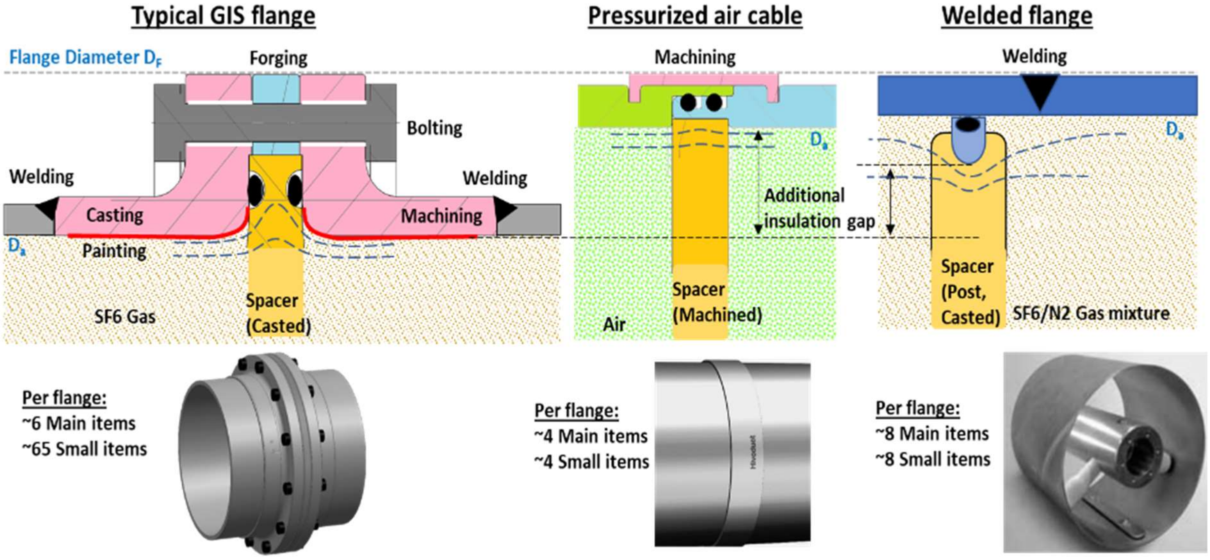


Fig. 4: Comparison of flange designs: GIS, PAC, Welded flange (picture from [2]).

The new flange design is protected by international patents.

The flanges are shown with the same outer flange diameter D_F – as this is the dimension which determines space requirements for installation. The manufacturing steps are provided for the main items. The symbolic equipotential lines (dashed) indicate the "smoothness" of the flange design regarding dielectrics. The number of items required to assemble one complete flange & spacer are provided as an indicator for manufacturing and assembly effort.

A detailed comparison of the flange characteristics is given in Tab. 2.

Characteristic	GIS Flange	PAC flange	Welded flange
Insulation gas, pressure	SF6, <= 7 bar	Air, <= 11 bar	SF_6/N_2, <= 6 bar
Process steps required for manufacturing and assembly	Welding, Casting, Machining, Forging, X-Ray test, Bolting (+Torque), Painting	Machining, Assembly	Welding (On site), X-Ray test or UTPA, Machining, Casting (Post), Assembly
Items per flange	~71	~8	~16
Number of sealing surfaces per flange	2	1	0
Number of seals per sealing surface	1	2	n/a
Type of gas sealing	Axial sealing squeezed by bolts.	Radial sealing on machined surface	n/a
Space requirement for flange: D_F-D_a	60-100 mm	24 mm	16 mm
Additional insulation gap	0 (reference)	~ 35 mm	~ 20 mm
Dielectric flange shape	Distorted	Smooth	Distorted
Forced alignment of enclosures	No	Yes	Yes
Electrical connection of enclosures	Via Bolts and forged ring	Via Ring. Contact force by pressure	Welded connection
Axial fixation of spacer	Yes	Yes	No
Surface quality on inside of flange	Casted surface: Requires painting	Machined surface	Welding seam.
Can be disassembled?	Yes	Yes	Cutting required.
Particle trap included in flange	No. Optional separate item.	Yes. Each side of spacer.	No. Separate item.

The comparison in Tab. 2 shows, that the new PAC flange design has improved technical characteristics and avoids the main issues known for existing GIL products.

The additional insulation gap provided at the same outer diameter and the smooth dielectric shape are specifically advantageous for the the use of pressurized air – to compensate for its reduced intrinsic dielectric strength compared to other insulation gases. It also results in much smaller capacitance per m as given in Tab. 1.

Pressurized air cable components

For PAC installations, a variety of components are required to be able to connect and interface all possible layouts required by project engineering. Tab. 3 provides an overview on the component portfolio, and it's use and characteristics.

Every component per enclosure size uses the same flange as shown in Fig. 4 as interface – to freely combine them as needed.

Tab. 3: Component’s portfolio of a PAC product.

Component	Use	Characteristic
Straight busbar	Long, straight connections	Flexible length: 200-5000 mm
Bushing	Interface to air-insulated lines	Various pollution classes & flashover distances
Length compensator	Compensate thermal expansion	<= 80 mm shrinking – compensates ~ 100 m straight bus
Angle piece 0-60°	Enable various angles	Any angle by machining
Angle piece 90°	Enable 90° turns	No bending radius
Flexible angle <10°	Added between long straight tubes as flexible connection	Makes an installation flexible like a cable
Air filling equipment	Air filling, pressure check	Standardized ½ inch items
Transformer connection	Interface to transformer	Direct adapter
Cable connection	Interface to HV cables	Plug type connection
GIS connection	Interface to GIS	1ph direct adapter
Compartment spacer	Separates air compartments	Allows differential pressures during installation & air filling

The maximum distance between two supporting spacers in a busduct is limited by the sagging of the conductor and by forces in case of short-circuit currents. Fig. 5 shows the sagging of aluminium conductors due to its weight and depending on the distance between its spacers for typical conductor dimensions. It is analytically calculated: both sides supported ring-shaped conductor with distributed weight.

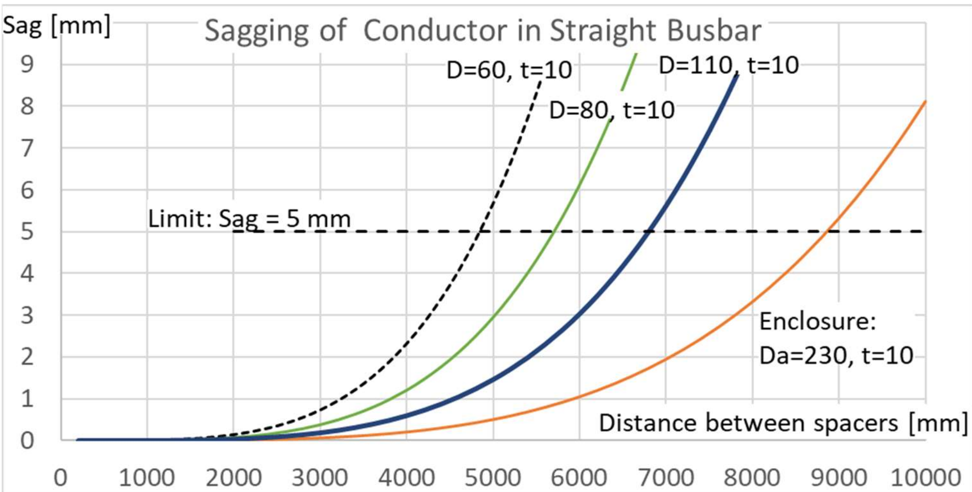


Fig. 5: Sagging of conductor and enclosure as a function of distance between spacers

Limiting the conductor sagging to 5 mm in the middle results in a maximum distance between spacers of ~5.5 m for a conductor with D=80 mm and thickness t=10 mm. The larger the conductor diameter the less sagging occurs – see the enclosure tube in Fig. 5 for comparison.

Therefore, straight PAC bus components have a flange with support spacer every 5 m, which together with small connection items gives the maximum transport length.

Bursting pressure tests and internal arc fault pressure

Bursting pressure tests were performed as witnessed test according to SVTI 704 [12].

The required bursting value p_B is derived for PS=10 bar (= $11_{bar,abs}$) acc. Table 402C for wrought aluminium alloys:

$$\text{SVTI 704:} \quad p_{B,req.} > 1.1 \cdot 2.8 \cdot 10\ bar = 30.8\ bar \qquad \text{Eq. 4}$$

To account for the new flange design, an additional safety margin was applied and all components were successfully **tested for $p_{B,test}$ > 50 bar**.

During an internal arc fault event, PAC shall experience a maximum pressure which is below the bursting pressure of its enclosures. Fig. 6 shows the result for the simulated maximum pressure during internal arc fault at 40 kA for 500 ms as a function of compartment length.

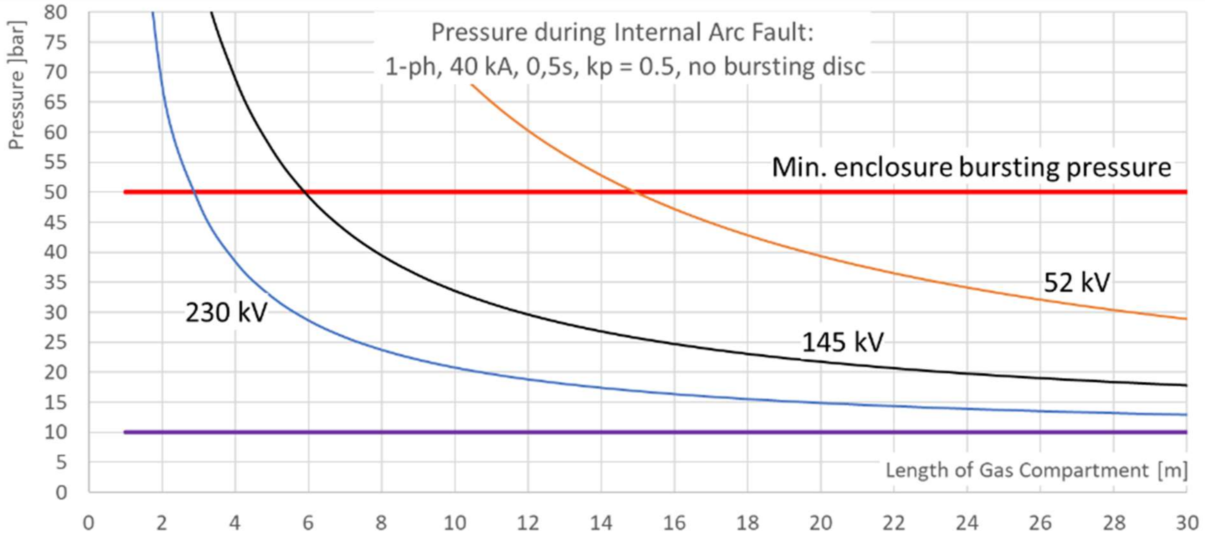


Fig. 6: Simulated maximum pressure during internal arc fault vs. enclosure bursting pressure

The inside pressure remains below the bursting pressure, if the gas compartments are longer than 15 m. This minimum compartment length is given by the placement of barrier insulators instead of support insulators. It is set as engineering condition and can be met for all PAC installations. Similar results and provisions are given in [2] p74ff.

As no rupture discs are used, hot gases from an arc fault remain inside. This is a significant safety advantage for PAC compared to GIS or HV cables and enable installations in proximity to other linear infrastructure, where people or equipment would otherwise be affected.

Test results: AC and BIL testing

Several test series as development tests and type tests have been performed on PAC to confirm dielectric properties as required by standard IEC62271-204.

Fig. 7 shows a summary of BIL tests on the 145 kV cable. Some test series were performed with given pressure and increasing voltage until breakdown (see vertical data points). Others were performed using same impulse voltage and reducing pressure until breakdown (horizontal data points). The resulting breakdown voltage is compared to the dimensioning breakdown voltage acc. to Eq.1 and shows a good fit over the whole pressure range. Negative polarity tests generally showed around 10% less breakdown voltage than positive impulses due to the well-known polarity effect. Similar test series have been performed for AC voltage and for other PAC products.

Comparing the breakdown voltage trendline to 145 kV $AC_{peak\ phase\text{-}to\text{-}ground}$ voltage of 118 kV in Fig. 7 indicates, that operation down to 2 bar is possible with reduced margins. Therefore, a pressure loss during operation does not immediately lead to failing insulation. This provides time for de-energization in the rare case of a leakage (if e.g., accidentally drilling a hole into the enclosure).

For example: In a gas compartment with 15 m length, it takes ~ 3 min to reduce the pressure from 11 bar to < 2 bar through **a hole with D=6 mm**. This time increases proportionally to compartment length.

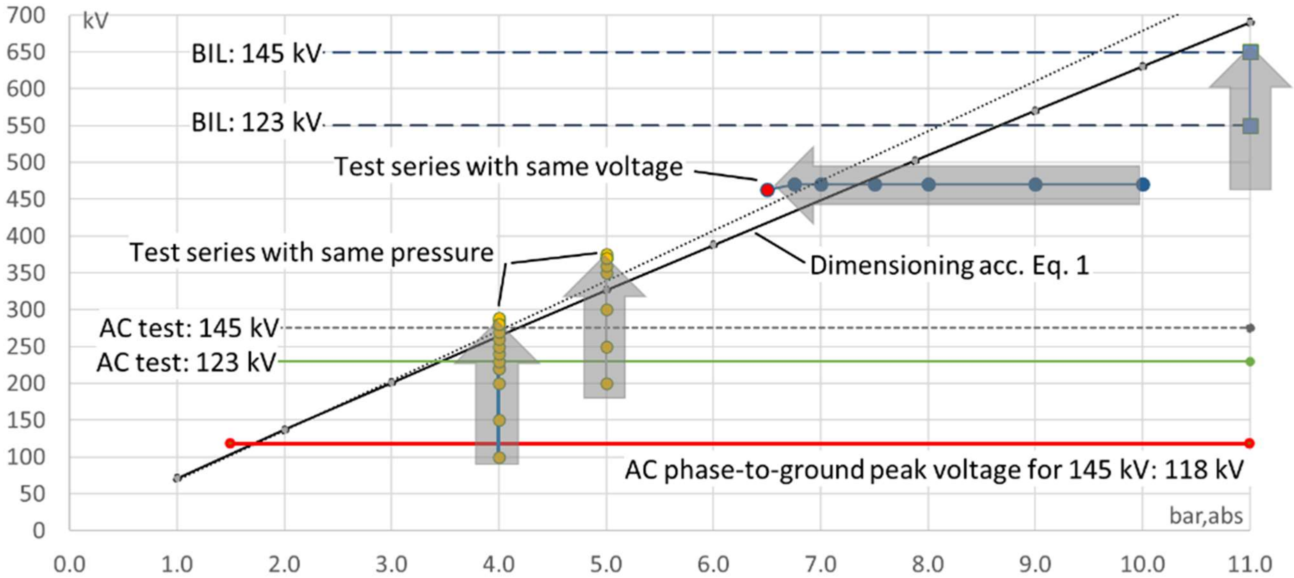


Fig. 7: BIL test results for pressurized air cable 145 kV compared to dimensioning acc. Eq. 1

Dielectric testing has been performed with and without evacuating air from the enclosures before filling with (dry) technical air. In most cases, rinsing the test pole with technical air from an inlet on one end to an outlet on the other end is sufficient and evacuation is not required. However, in high humidity conditions during assembly, evacuating most of the moist environmental air before filling is suggested. Alternatively, dry heating can be applied.

Test results: Temperature rise testing

A 145 kV test pole with bushing, straight busbars, angle pieces and covers was equipped with temperature sensors on the conductors, contacts and enclosures to measure the temperature rise during continuous current flow at various operating air pressures from 1 to 11 bar.

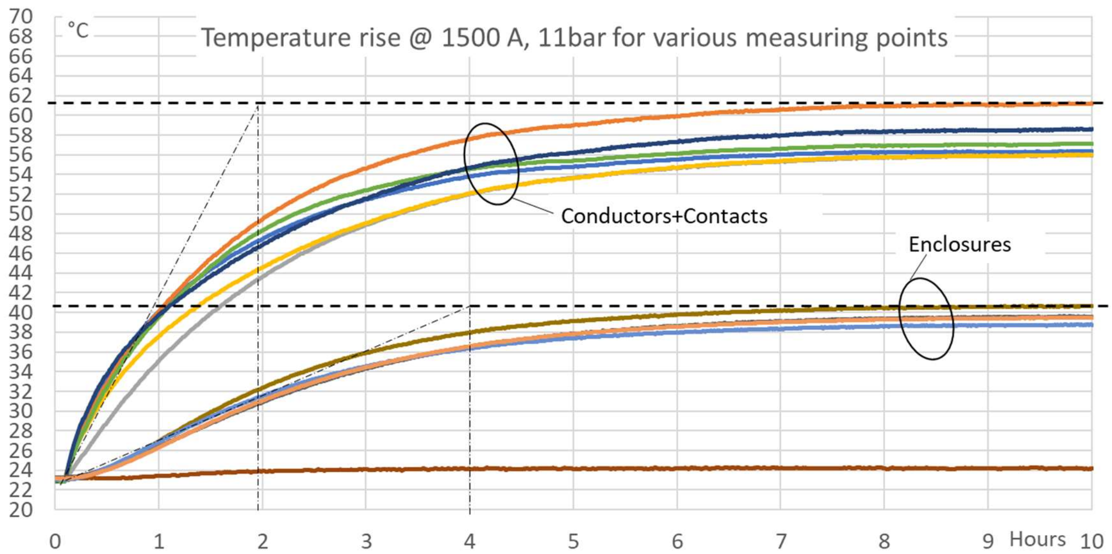


Fig. 8: Temperature on conductors and enclosures for 1500 A continuous current over 10hrs.

Fig. 8 shows examples of temperature rise at 1500 A and 11 bar on various measurement points on the conductors (showing a time constant of ~2hrs) and enclosures (time constant ~4 hrs). Enclosure temperatures stay below ~41°C at 1500 A continuous current.

Fig. 9. shows a compilation of steady-state temperatures for different currents and with currents in conductor + enclosure and in conductor only.

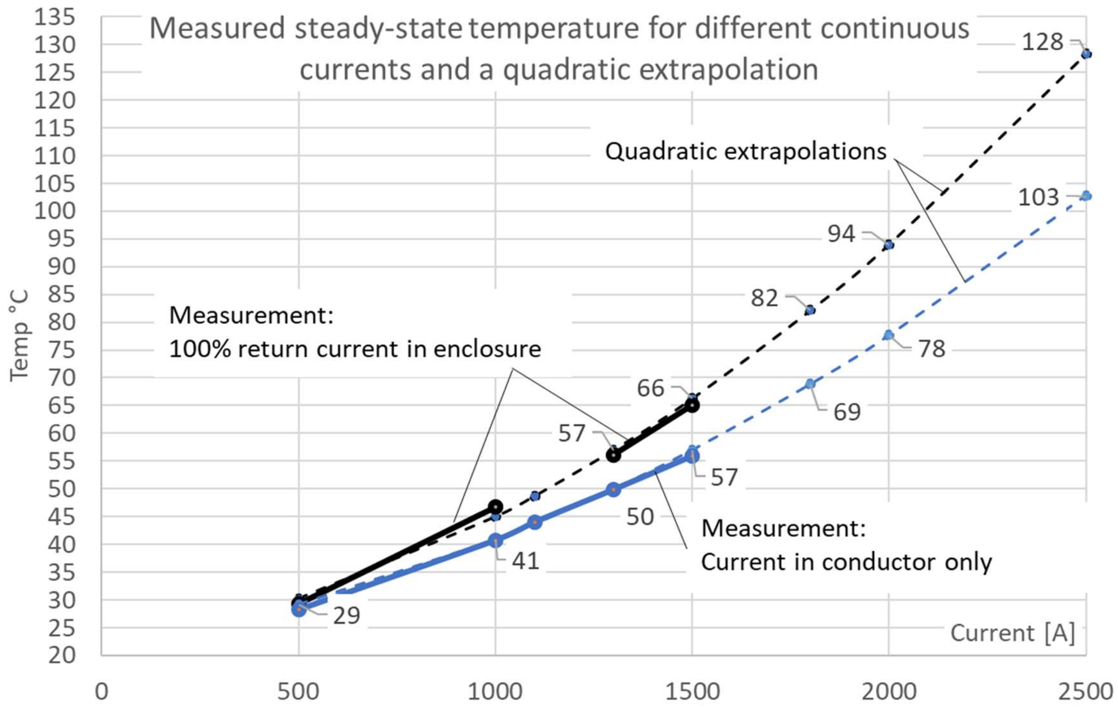


Fig. 9: Steady state temperature on conductor during continuous current test with 100% enclosure current (Top) and 0% enclosure current (Bottom).

Fig. 9 shows that a long busbar conductor reaches a temperature of 66 °C at 1500 A with 100 % enclosure current. Without enclosure current, this temperature reduces to 57 °C, see Fig. 8. Quadratic extrapolations of the measurements (full lines) using $T(i) = 0.000013 \cdot i^2 + 0.01 \cdot i + 22$ (dashed lines) conclude, that on long busbar conductors the limit temperature of 100°C is reached at ~2100 A current over > 8h, whereas enclosures remain < 65°C.

Installation options for pressurized air cables

Exit busducts for GIS are mostly mounted on elevated steel structures. Existing GIL systems are installed in tunnels or (rarely) directly buried in soil. Tunnels and elevated steel structures can similarly be used for pressurized air cables. However, the components and system design for PAC additionally allows for **installation in confined spaces** like pipes or microtunnels.

Fig. 10 shows possible installation options – which can comprise one or several parallel systems. The single-phase enclosure allows triangular and side-by-side arrangements of the phases for best fit to the installation option and similarly allows single-, two-, or three phase systems.

The compact, triangular arrangement with a proprietary roller system allows to install segments of PAC into a pipe with D_{pipe}>=600 mm – starting and ending at a manhole, see an example in Fig. 11. A HV line section is continued underground using PAC to pass below a residential zone or mountain or other obstacles. This simplifies finding a possible corridor for an HV line as critical sections can be tunnelled using PAC.

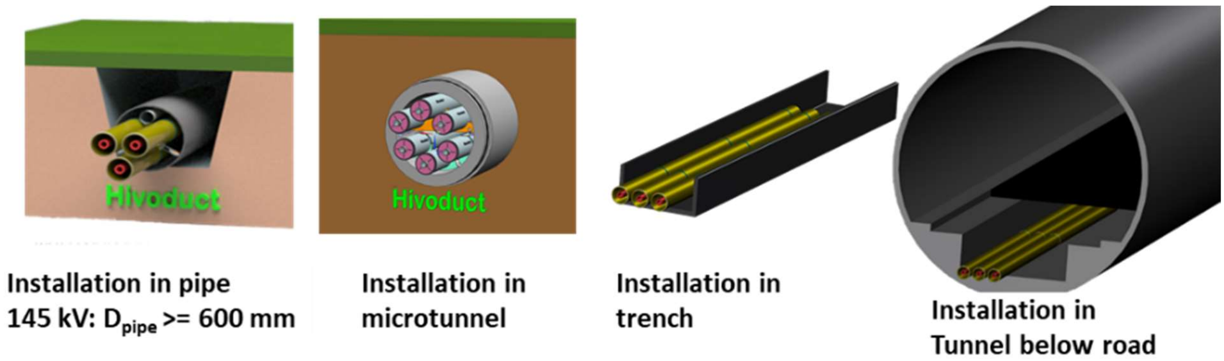


Fig. 10: Installation options for PAC: Compact (two left) and standard (right).

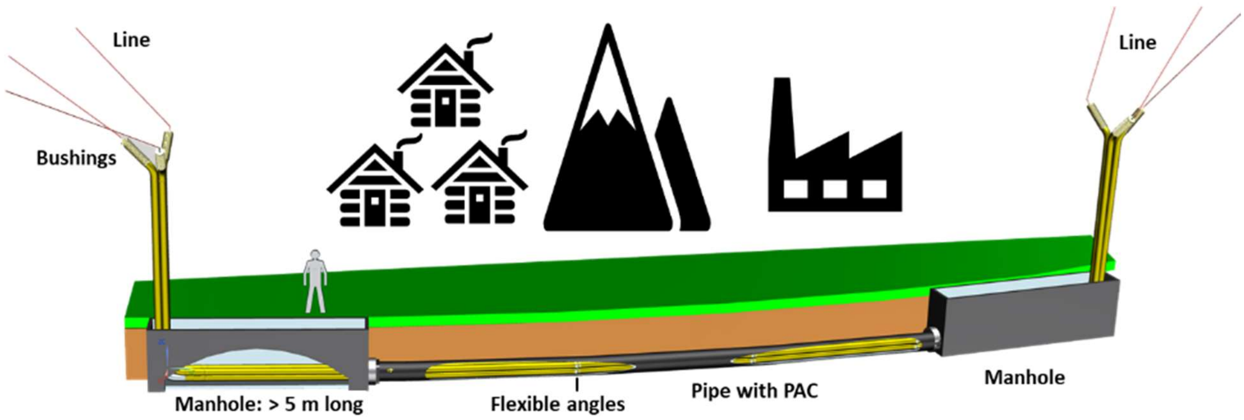


Fig. 11: Installation example: Underground section of a line using PAC.

Dimension examples for compact installations acc. Fig. 10 are shown in Fig. 12. Three phases of PAC are placed in a pipe (left) or microtunnel (right) including a roller system for installation and revision. The roller systems with wheels remains in the pipe during operation and supports thermal expansion movements as well as quick removal for repair.

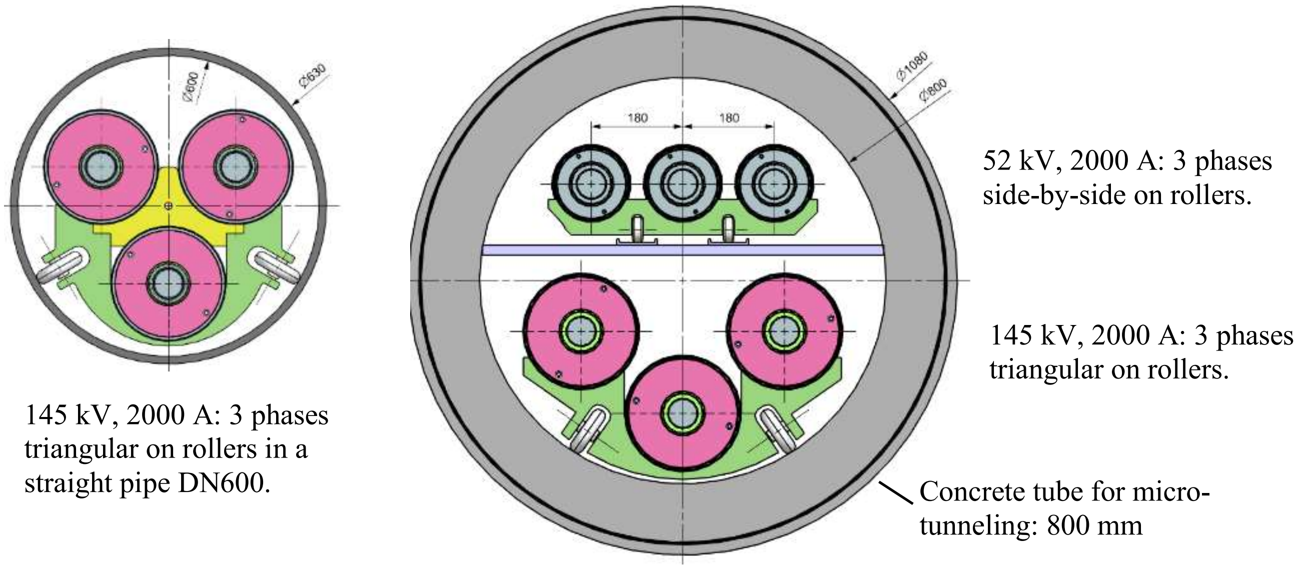


Fig. 12: Dimension examples: PAC arrangements in pipe (left) and micro-tunnel (right).

Technologies and trenching for pipes and microtunnels with a diameter 0.6 – 2 m are well established construction technologies used for water supply, sewage systems and HV cables. Main advantages of PAC in most use cases are: Lower capacitance per m, reduced losses (see Tab. 1), non-visible (underground), no noise emissions, lowest outside magnetic fields [2], non-flammable aluminium enclosure, all earthing options, and zero GWP.

Conclusion

It is concluded that pressurized air cables based on the new flange design were successfully developed and tested for medium and high-voltage applications ranging 12 kV to 145 kV. Due to the compact new flange design, the resulting product dimensions are like products using SF_6 or alternative gases. Applying the roller system for installation requires smaller corridors and less construction effort and enables installations into pipes and microtunnels.

Scaling and prototyping for voltage levels 245 kV and 420 kV has been done and product feasibility confirmed for these voltage levels while type testing is still pending.

Therefore, pressurized air cables are a viable option for high-voltage electric energy transmission with reduced environmental impact and improved technical features.

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