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Emerging asset management strategies for OF cable technologies in North America

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SUMMARY

North American utilities started putting transmission lines underground as early as 1930s. Oil-impregnated paper insulation (OF) was state-of-the art technology utilized by cable and cable accessories manufacturers, and for decades has been deployed by electrical utilities and industrial customers to build their UG transmission grids.

OF cables and their accessories – terminations and joints - have been proven as highly reliable in operation, with great longevity that often resulted in service life way longer than typical 40-year industry accepted span.

In US and Canada (and with some installations in Mexico) this technology became a backbone of the UG transmission grid for voltage levels 69 kV to 345 kV, with an estimated 3,000 – 3,600 circuit miles (4,800 – 5,800 km) still in operation. Most of these UG lines are built as high-pressure fluid filled (HPFF) cable systems, commonly known as pipe-type cable systems. These systems consist of 3-c cable cores (without external jackets) pulled in the steel pipes that are directly buried in the ground.

Today this ageing pipe-type cable infrastructure requires maintenance to be operated safely and reliably, but faces increasing challenges: dwindling number of niche manufacturers is affecting availability and lead times of spare parts; pipe-type projects require skilful workforce and special equipment; despite excellent dielectric performance of the cables and accessories, there are still operational issues like fluid leaks due to pipe corrosion and loss of material.

UG pipe-type asset managers and other stakeholders in US and Canada are exploring innovative approaches for maintaining reliable power transmission at an acceptable cost as pipe-type lines are gradually reaching end of life.

This paper is an attempt to categorize different strategies under consideration and deployment in North American UG cable and cable accessories industry, and will discuss differences, advantages, shortcomings and future developments that asset managers and other stakeholders are considering going forward.

KEYWORDS

Oil-filled (OF) cable systems, terminations, joints, pipe-type cable systems, transmission asset management strategies, transition joints

1. INTRODUCTION

Oil-filled cable technology in North America - oil-impregnated paper insulated cables, terminations and joints - has been deployed since 1930s with an excellent track record. It provides power to North American large metropolitan areas, municipalities and industrial customers at voltage levels from 69 kV through 345 kV, and it generally can be divided into self-contained fluid filled (SCFF) systems and high-pressure fluid filled (HPFF) systems, the latter commonly known as pipe-type cable systems.

Today there is an estimated 3,000 to 3,600 circuit-miles (4,800 – 5,800 km) of these systems in operation, with thousands of transmission class terminations and joints. Most of the circuits are pipe-type systems, with three paper-insulated cable cores pulled in the steel pipe and pressurized with dielectric fluid - oil or gas.

Asset managers value this technology due to its robustness, reliability and longevity that commonly exceeds industry accepted 40-year life for cable systems.

Comparing to modern solid dielectric cable systems, pipe-type systems are quite elaborate, with corrosion prevention systems for steel components and auxiliary equipment for maintaining and managing the fluid.

Pipe-type system is pressurized with dielectric fluid under high pressures, typically 200 psi – 400 psi (14 – 28 Bar), and beside the cables, terminations and joints, it consists of steel pipes and necessary auxiliary equipment to maintain the pressure and fluid flow – e.g. pumping stations, reservoirs, returning oil lines.

Different concepts, voltage classes and applications for outdoor terminations and for connection to GIS and transformers are shown in Figure 1.

Terminations for pipe-type cables have generally more complex design than their counterparts for solid dielectric cables, as they need to contain high fluid pressures while filtering the fluid from the pipe system and preventing any contaminants coming in the high electrical stress zones inside the termination body.

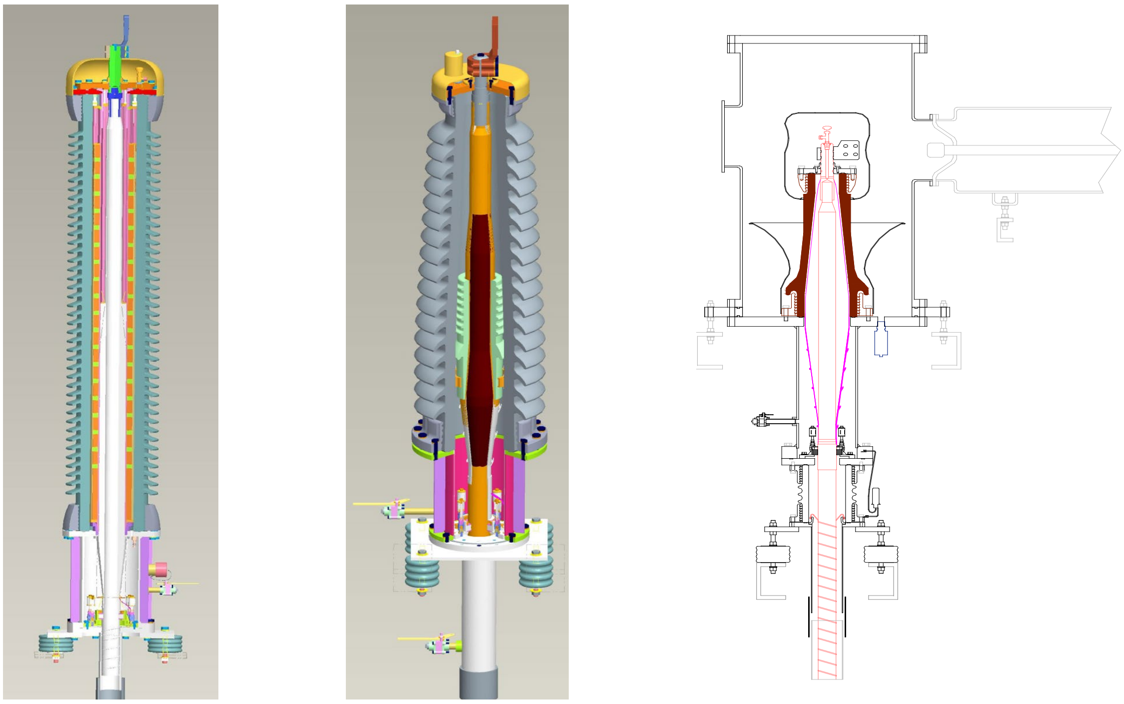

Figure 1 : Transmission class terminations for pipe-type cables – with capacitor graded design (left), inner stress control insulator (middle) and for connection to GIS and transformers (right)

Stress control is typically achieved by oil-impregnated paper cone specifically designed to address longitudinal component of electrical stress, which is critical for laminar dielectric systems.

State of the art designs for voltage classes 230 kV and 345 kV also use stacks of donut capacitors connected in series, that slide over the cable and provide additional reduction of stress in air, allowing for smaller external porcelain insulators.

Typical designs of normal joints for pipe-type cables feature three fully screened cores contained in steel housings under oil or gas pressure. Distribution of electrical stress is controlled by hand applied oil-packed tapes per the calculated steps and threads for the specific cable. Additional critical aspect is longitudinal stress at the connector, where stepping of the paper insulation also needs to be calculated.

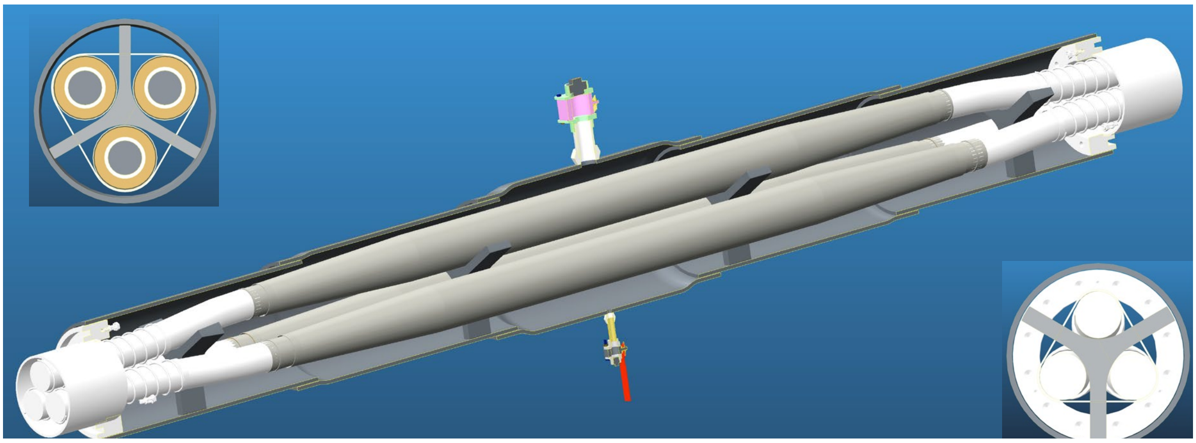

Figure 2 : Typical design of normal 3-c pipe type joint with reducers, spiders, three cable cores in 5-piece housing

Even more so than for the pipe-type terminations where some designs feature factory controlled perforated paper rolls, skilled force and workmanship is crucial for building quality pipe-type joint in the field.

Some of pipe-type circuits have been in operation for 60 years or more, and as they age, they will require extensive maintenance, refurbishment and eventual replacement.

This presents a complex problem for the stakeholders – asset managers, construction companies, manufacturers and general public, which calls for industry to take up on the challenge and find the options to increase ampacities of underground circuits at a reasonable cost and mitigate any negative aspects of conversion activities.

2. EMERGING STRATEGIES

To address this set of challenges, asset managers are increasingly looking in creative ways and emerging technologies with short and long-term goals in mind:

- To extend the life of underground transmission pipe-type assets and avoid or postpone costly capital investments
- To increase the ampacities of the lines and integrate power generation from new renewable energy resources
- To mitigate fluid leaks due to corrosion, prevent catastrophic failures and reduce operational costs
- To minimize or eliminate disruption to normal public life that is often associated with underground conversion activities in metropolitan areas

Over the years set of asset management strategies related to maintenance and conversion of pipe-type cables, terminations and joints have emerged and are in different stages of deployment:

- Traditional approach - Replacement of pipe-type cables and accessories with same technology
- LPP upgrades – Replacement of OF cables with LPP insulated cables
- Transitional approach – Replacing part of OF line with solid dielectric technology
- Full conversion – Full replacement of OF cables by solid dielectric ones

2.1. Traditional approach – Replacement of oil-filled cables and their accessories with the same technology

When there is no need for increased ampacity of the line, the main drivers for replacement are relocation of existing circuit, addition of a new circuit, or replacement of leaking or otherwise damaged section with frequent issues.

Considerations for these types of projects include technical parameters like ampacity, existing pipe sizes and their condition, installation limitations, but also the availability of replacement parts and lead times, which, in many cases, has become a bottleneck.

Specific challenges with this strategy include:

- Identification and specification of the existing installed equipment - cables, terminations and joints
  In many cases asset managers don't have accurate technical documentation on the underground pipe-type system, as some of these lines were installed many decades ago, and due to its reliability and longevity did not require major maintenance and attention. Experienced staff may have transitioned to retirement and old drawings and other documentation may not have been digitalized and are not available.
- Availability of skillful workforce
  OF technology has reached its maturity and is gradually being replaced with solid dielectric cable systems, and qualified personnel – field technicians and jointers – have become a scarce resource. Due to a large installed base in US and Canada this specialized labor force is available in North America through a handful of installation companies and freelance jointers.
- Availability of replacement parts
  In pipe-type segment in North America there is one cable manufacturer and three to four accessory manufacturers who are serving the market, and lead times and availability of the parts that are compatible with customers' legacy systems can be a bottleneck for the project. To help the situation, few of the accessory manufacturers have developed replacement and retrofitting programs with high level of customization. Still, this area is a challenge that needs to be considered.

In conclusion, replacement of OF paper with the same technology is a traditional proven strategy that is still deployed but to limited extent; it is used in cases where existing HPFF paper circuits are not expected to grow in load and where cost of maintenance does not justify capital investments required for conversion to solid-dielectric technology.

2.2. LPP upgrades - Replacement of oil-filled cables and their accessories with LPP technology

Development of Laminated Paper Polypropylene (LPP or PPP) insulation provided an excellent option for retrofit of Kraft paper cable circuits.

LPP technology offers lower dielectric losses than conventional paper, resulting in smaller cable diameters and pipe sizes, with longer cable pulling lengths and fewer manholes and joints. Comparison of critical dielectric properties between Kraft paper and LPP is shown in Table 1.

Table 1. Critical dielectric properties for Kraft paper and LPP

Dielectric property	**Kraft paper**	**LPP**
Permittivity	3.5	2.8
Dissipation factor	0.23%	0.07%
AC breakdown strength	50 kV/mm	50 kV/mm
BIL breakdown strength	130 kV/mm	150 kV/mm

In some cases, LPP can reduce cable insulation wall thickness by up to 50%; therefore, increasing the ampacity of the line by using a larger conductor. This is a very popular and cost-effective method that provides the benefit of utilizing existing pipe-type infrastructure including reservoirs and pumping stations while increasing the ampacity of the circuit.

LPP has been effectively used for new HPFF installations since the mid-80s. However, its major application, that no other technology to date has been able to match, is the retrofitting (known as “re-cabling” or “re-conductoring”) of older paper circuits, where the ampacity of the line can be increased within the existing pipe size.

Terminations and joints for LPP cables are similar in design as traditional Kraft paper insulated devices, but the stresses are different and must consider difference in dielectric properties between LPP and Kraft paper.


Figure 3 : Installation of 345 kV LPP joint – shielding of the connector (left), template for the stress cone slope (right)

This maintenance strategy faces some of the same challenges as the “paper-to-paper” replacement strategy: identification of the existing installed HPFF base, lead time for the components, and availability of a skilled labor force.

Most of these issues can be mitigated through proper planning and scheduling of replacement projects. To facilitate this process for the end-users, some of the North American suppliers of OF cable accessories have developed customized programs for preventive maintenance and replacement based on age and condition assessment of customers’ pipe-type circuits.

This approach has produced very good results, significantly extending the life of pipe-type assets and eliminating costly tear downs of pipe-type infrastructure and full conversion to solid dielectric technology.

2.3. Transitional approach – partial conversions to solid dielectric technology

If there is a need for extending OF circuit, or replacing one ailing section with frequent issues, partial conversion from OF to solid dielectric technology can be achieved with transition joints.

This is another tool for asset managers to extend the life of existing OF circuits by partially converting OF sections to extruded. There have been several projects in recent years that utilized this approach. This is especially true for 3-c cable systems, where there are less constraints than with pipe-type cable systems in terms of pressures, space, and ampacities.

As North American HPFF asset managers are increasingly looking into this option, there has been a lot of activity on the design, standardization, and supply side, with a couple of major design approaches established over the years.

Ongoing work in IEEE standard for transmission class terminations and joints attempts to classify different designs and create qualification programs that can be used for more effective and wide spread utilization of these devices in North America.

One of the most common is the “back-to-back” design, where existing, field proven technologies are put together in a compact arrangement.

This design was used in couple of recent projects in the US, including 2019 retrofit in “Providence River relocation” project, where 2.3 miles long 115 kV SCFF circuit was retrofitted with solid dielectric cables utilizing transition joints [4].

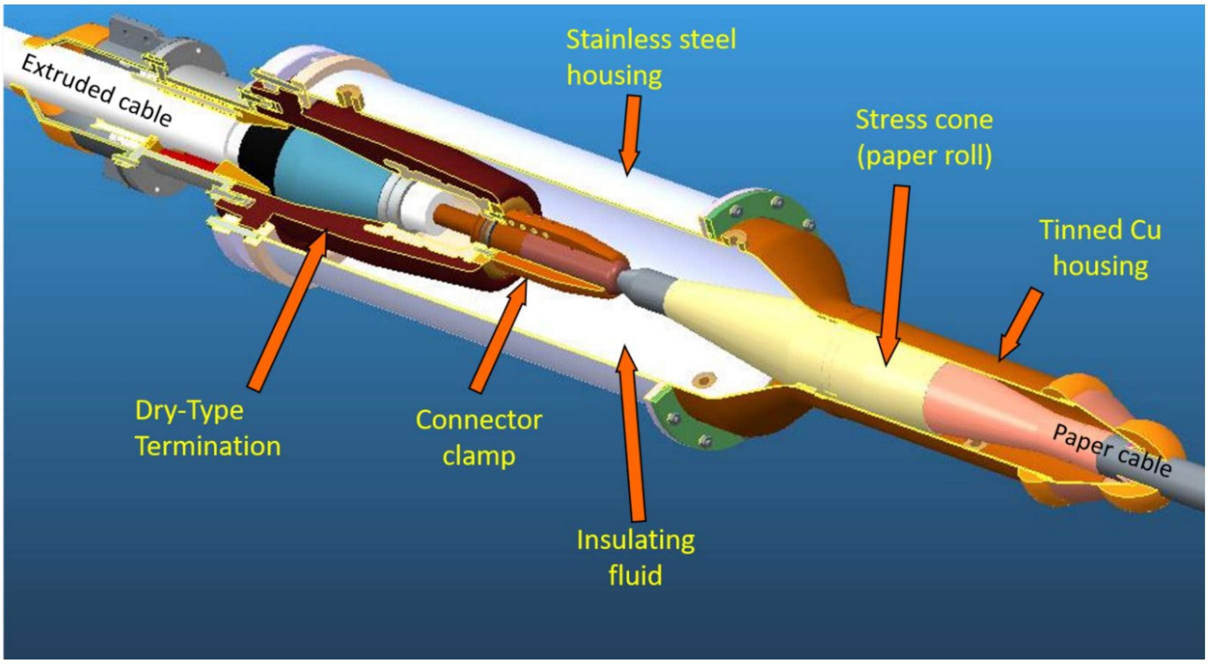

Figure 4: Example of 138 kV 1-c transition joint design in « back-to-back » arrangement

In conclusion, partial conversion strategy can be effective option for asset managers to extend the life of an old OF circuit and boost the return of an existing asset. It is not as widely deployed as the LPP strategy, but it is becoming more common and is expected to grow, especially in pipe-type circuits.

2.4. *Full conversion – Replacement of oil-filled cables and their accessories with solid dielectric technology*

The ultimate challenge for the industry is to find the ways to effectively utilize existing pipe-type infrastructure to integrate solid dielectric cable technology and eliminate fluid related issues.

This approach is in its infancy due to set of technical challenges that will be discussed here, but also due to high reliability of pipe-type systems and dependency on them. The vast majority of UG transmission infrastructure is built with pipe-type cables that are still delivering power to where it's needed.

The main value proposition of the full conversion strategy is to utilize existing circuit routes with buried pipes for pulling out old OF and pulling in new solid-dielectric cables, avoiding costly excavations and other construction activities that are associated with new UG installation. In large metropolitan areas in the US and Canada, it is hard to imagine any other option for replacing old HPFF circuits that would be possible or feasible.

Cable pipes used for transmission class cables come in different sizes, generally depending on the voltage level and cable size. Comparing to extruded cables with XLPE insulation, OF laminar cables have thinner insulation walls. XLPE cables have additional protective layers and the outer jacket, which amounts to overall diameters that existing pipe sizes typically cannot accommodate for.

Finally, having a fluid under the pressure in pipe-type systems allows for forced cooling of the lines, providing additional Amps when needed.

Table 2. Comparison in insulation thickness between XLPE, Paper and LPP insulated cables [2], [3]

Voltage level	XLPE Insulation Thickness (CS9)	Kraft paper insulation thickness (CS2)	LPP insulation thickness (CS2)
115 kV	15 mm	9.5 – 10.7 mm	6.3 mm
138 kV	18 mm	11.2 – 12.4 mm	6.9 – 7.6 mm
161 kV	20 mm	14.6 mm	-
230 kV	23 mm	15.4 – 18.9 mm	11.4 mm
345 kV	26 mm	23 – 25.9 mm	15.2 mm

As a result, full conversion typically cannot support the same or higher ampacity of the circuit. This is especially true for transmission classes 69 kV - 230 kV.

One of the factors that can somewhat alleviate the problem is the design of the bonding and grounding system. With proper system designs, it is possible to match to or even increase the existing ratings of majority of the circuits in service.

There are different design approaches for solving ampacity constraints. One common direction is looking into the development of dielectric materials which would enable higher electrical stresses and temperatures in extruded cables and their accessories, resulting in thinner insulation walls and smaller overall diameters.

There are a couple pilot projects that have been completed in recent years (e.g. 138 kV circuit retrofit described in [5]); still, more information and field experience is required for full adoption and market acceptance.

One emerging solution is the development of "hybrid" cable systems which combine well-known and reliable pipe-type components with customized extruded insulation systems and elastomeric stress control parts for joints and terminations [6].

Project currently in the workings with a major US utility will utilize a 115 kV "hybrid" joint that is a three-core device with special XLPE cables pulled in the existing pipe and spliced in existing pipe-type manhole. Most of the pipe-type features are there: steel casings with option to pressurize with Nitrogen, reducers, spiders with clamping system, and even a provision for fiberoptic cables for DTS and disturbance monitoring. Stress control joint bodies are premolded and factory tested like any regular solid dielectric cable joints.

Project is in the final design stages and implementation is expected in late 2022.

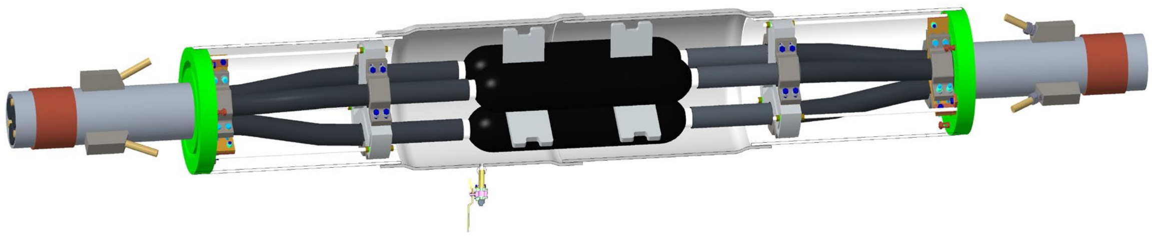

Figure 5: 115 kV 'hybrid' joint for XLPE cable in pipe-type infrastructure: three solid dielectric cable cores with clamping system and spiders, pipe reducers and opting for optical fiber

Full conversion strategy also requires some other considerations like differences in thermal and mechanical stresses and thermo-mechanical bending (TMB), condition of existing pipes, sizes of the manholes, cable pulling techniques - all of which play a role in the feasibility analysis for a full conversion option.

Despite mentioned challenges, full OF-to-solid-dielectric conversion strategy is the future of maintenance and replacement of pipe type cable systems. There are still considerable technological hurdles that need to be overcome until full adoption by the market.

A significant R&D effort is currently working towards this goal, and we expect to see solutions like high-stressed extruded cables and hybrid pipe-type /solid- dielectric systems to fully emerge and go into widespread field implementation.

3. DISCUSSION

Underground transmission networks in North America still largely rely on pipe-type OF cable technology which has an excellent track record in terms of reliability and longevity.

Significant industry effort is being expensed in development of new materials that can take higher electrical, thermal and mechanical stresses, and in design of the accessories – terminations and joints that can advance partial and full conversion of pipe-type circuits.

While some pipe-type circuits will remain in operation for years to come, replacement and retrofit strategies are being discussed and deployed for those that are reaching their end-of-life.

The four approaches discussed in this paper include the maintenance of existing circuits by using the same OF technologies, partial upgrades by utilizing LPP technology, partial conversions with transition joints, and full conversions to solid-dielectric systems.

These strategies are in different stages of deployment and industry acceptance, each with its own set of advantages and shortcomings. They can be used in parallel and in combination, depending on the specific field conditions and user requirements.

It is expected that transition of pipe-type systems to retirement will be gradual while industry is optimizing the path forward.

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