Power Cable Systems Design Evolution in the United States from 1996 to 2020

JC **HERNANDEZ**, Diana **RAMIREZ**, Caryn **RILEY;** GT-NEETRAC, USA, jean.hernandez@neetrac.gatech.edu, diana.ramirez@neetrac.gatech.edu, caryn.riley@neetrac.gatech.edu

Essay **SHU**, Consultant, USA, essay.wenshu@gmail.com

Nigel **HAMPTON**, UL Solutions, USA, nigel.hampton@ul.com

ABSTRACT

Developments in cable designs have always been of great interest to both utilities and manufacturers. In 2003, Joe Dudas, with support from utility bodies (AEIC & NRECA), finished several surveys to establish industry trends in medium voltage (MV) cable. The results of these surveys proved to be very useful to utilities and manufacturers in understanding markets and trends. In 2016 and 2021, the authors undertook two sequential utility surveys respectively on cable, materials, and accessories to all interested parties. These surveys expanded the work conducted by Dudas to a 25-year trend, and thus providing perspective on present day MV cable and accessory usage in the US.

KEYWORDS

Design, MV, Benchmarking, Extruded Cable Systems.

INTRODUCTION

Power cable systems have become a ubiquitous feature of modern society. They are responsible for delivering electricity from power stations to homes, businesses, public buildings, and critical infrastructure. They have undergone significant evolution since their inception in the late 19th century, with advances in technology and materials driving improvements in design and performance.

The earliest power cables were made of paper insulation lead-covered and had limited voltage capacity. These cables were mainly used for low-voltage applications, such as lighting and powering small motors. In the decade of 1920, synthetic materials, such as rubber and polyethylene, were introduced as insulation materials. These materials provided higher voltage withstand capability that allowed for improved performance and reliability. The use of synthetic insulation materials was one of the most significant developments in power medium voltage cable system design [1], as it allowed for higher power to be delivered over longer distances, which incentivized their deployment.

In the 1960s, the development of cross-linked polyethylene (XLPE) and Ethelene Propylene Rubber (EPR) insulations marked probably the most significant advancement in power cable technology [1]. This type of insulation provided better thermal and electrical properties than traditional insulation materials, making it suitable for high-voltage transmission. This advancement in insulation technology led to the development of high-voltage power cables, which were used to transmit electricity over longer distances. High-voltage power cables have been critical in providing electricity to remote areas, such as rural communities and offshore oil platforms.

In the 1970s, the introduction of composite materials, such as glass fiber and aramid fibers, as strength components marked a significant improvement in power cable system design. The composite materials provided higher strength and flexibility than traditional ones, allowing for the production of lighter and more durable cables.

In the 1990s, with the advent of digital computers, computer-aided design (CAD) and finite element analysis (FEA) software became prevalent in power cable system design. CAD and FEA software allowed designers to create and test cable designs in a virtual environment, reducing the need for physical testing and generating optimal designs. This approach significantly reduced the cost and time required to develop new cable designs, allowing for faster innovation and commercialization.

In the 21st century, the focus of power cable system design has been on improving efficiency and sustainability. New insulation materials, such as silicone rubber, are been explored, which may offer improved thermal and electrical properties while also being environmentally friendly. The development of renewable energy sources, such as wind and solar, has promoted the development of dc cables for both medium voltage and high voltage applications. They will allow deliver electricity over long distances, e.g. from offshore wind farms to the mainland grid.

Prior work in the area of power cable system design evolution in the USA was initiated by Joe Dudas and supported by the AEIC and NRECA [2]-[7]. The work was aimed to establish industry trends in medium voltage (MV) cable usage. His work started in 1993 [2] with findings reported approximately every 5 years until 2003 [7]. The information collated by Dudas proved to be useful to utilities and manufacturers in understanding technical specification trends and installation practices. The work reported by Dudas only considered cables. With technology evolution and changes in utility operations, the results from the 2003 survey are now likely inaccurate.

Therefore in 2014, the authors launched a baseline project to continue and update the work by Dudas pertaining to Investor Owned Utilities (IOU) and electric cooperatives (co-op) [8]. This paper reports on the next iteration in the NEETRAC's effort to capture the continuing evolution of MV underground cable system construction and usage from 2014.

APPROACH

Previous Studies

Prior work in this area was performed by Joe Dudas and supported by AEIC and NRECA [2]-[7] to establish industry trends in medium voltage cable usage (15 kV to 35 kV). His work started in 1993 and updated approximately every 5 years until 2003. Essentially identical questions were asked in each of the surveys allowing trends to be derived. The results were reported separately for investor owned utilities (IOU) and cooperatives (co-ops). The information collated was useful to utilities and manufacturers in understanding technical specification trends and installation practices. The last survey was conducted in 2003 by Dudas. With technology evolution and changes in utility operations, the results from the 2003 survey are likely outdated.

Additionally, the work conducted by the authors in 2014 [8] project was a continuation of the work reported by Dudas.

This Study

The work reported here sought to review and analyse the raw data from the previous surveys and re-establish the survey to determine today's usage trends. Previous surveys before 2014 focused on cables only. A number of issues with accessories were also explored. This study covered not only cable designs, but also included accessory and connector designs, installation practices, and the use of rejuvenation. Investor owned utilities and co-op data were reported together. This paper provides a 2019-2020 benchmark on utility cable and accessory specifications and extends the 10-year technical specification trend developed by Dudas to a 25-year trend.

METHODOLOGY

This project continued to deploy a similar methodology to the one used by Dudas; namely, collating utility specifications and surveying to establish purchasing data and impressions.

Data Collection

Cable specifications, typically issued by utility standards group, were requested from utilitiy members. These documents usually specify permissible cable constructions, proper cable identification, and the required testing for specific applications. A subject matter expert extracted information from each cable specification document and then populated a database. Each utility was also requested to supply the cable length purchased in 2019 to reflect the cable/accessory demand. Approximately, 1,500 entries with to the industry, i.e. cable designs, cable replacement practices, and accessory design. The specific areas examined in this study appear in [9]. Papers published by Dudas based on the 1993, 1999, and 2004 surveys as well as the work reported in 2019 [8] were also consulted to establish the 25-year trend.

RESULTS

One hundred twenty-five (125) utilities participated in this study (2019-2020), of which 34 were IOUs and 91 were electric co-ops. In this context, each operating company is counted as a utility. The total reported length of the study presented here is approximately 87 million feet (~16,518 miles). The statistical margin of error for this study was approximately 10% with a 95% confidence level based on participation compared to the whole utility base. Results for different cable characteristics are shown in the next subsections.

Voltage Class

The most commonly purchased cables are 25 kV class. Nearly 52% of the purchased length (close to 8,500 miles) is 25 kV rated. Based on the MoE calculated for this study, the percentage of purchased length for 25 kV rated cables could be 42% to 62% (52% data, ±10% bars) as shown in Fig. 1. A little over 40% (44% +/- 10%) of the purchased length (approximately 7,200 miles) is 15 kV class, followed by 3% (250 miles) for 35 kV class. The least purchased cable is 5 kV rated, accounting for approximately 1% of the total purchased length (237 miles).

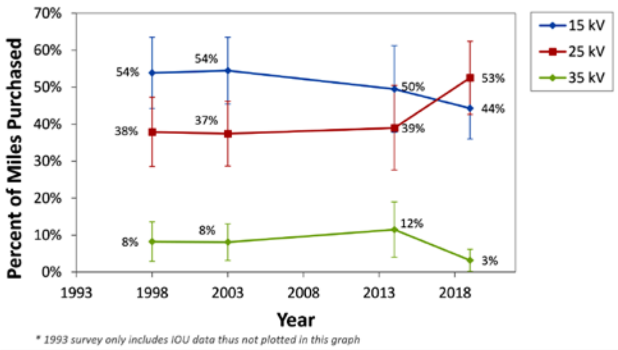

Fig. 1: The 20-Year Trend in Purchased Cable Length by Voltage Class including Uncertainty Bands from the MoE Estimate

Survey data also shows that the share of 25 kV class cables in purchased length increased over the past 5 years. The use of 15 kV class cables dropped approximately 6% compared to that of 5 years ago and following the tendency. On the other hand, the use of 35 kV cables has decreased from 12% to 4%. The magnitude of change is, however, within the margins of error of the results and thus not viewed as significant.

Conductor

Conductor Material

The majority of surveyed utilities specify both aluminum and copper conductors for different parts of their systems. A quarter (25%) of the participating utilities only specify aluminum conductor, which is more common in cooperatives. Aluminum composes the majority (82%) of IOU conductors and almost all (93%) the conductor material used by co-ops due to its lower cost as compared to copper. Copper conductors are more expensive and commonly appear in large conductors (> 500 kcmil) for feeders or #2 AWG conductors for important circuits to justify the cost.

Popular Size

The most frequently purchased cable has a conductor size of 1/0 AWG (53.48 mm^2), followed by #2 AWG (36.63 mm^2) and #1 AWG (42.41 mm^2). The total purchased length of these three relatively small conductors is approximately 60% of the total reported length. Approximately 22% of the reported cable length has a large conductor size (≥ 500 kcmil (253.4 mm^2)), which is most often used in system feeders. The three most commonly purchased large conductors are 1,000 kcmil (506.7 mm^2), 750 kcmil (380 mm^2) and 500 kcmil. The total purchased length for these three conductor sizes constitute about 80% of the purchased length for all large size conductors (larger than 500 kcmil).

Water Blocking Feature

Moisture is one of the most important factors for water tree initiation and development. The presence of water can be limited by preventing it from permeating down the conductor strands. In 2020, approximately 35% of purchased cables were solid and 50% strand-filled. Comparing with results from 2014, the use of conventional stranded conductors without fill had reduced from 30% to 15% in 2020.

Extruded Components

In the United States, it is a common practice for utilities to specify their requirements for extruded components. The next subsections show results for each of cable extruded component.

Conductor Shield

The conductor shield is a semi-conductive layer between the conductor and the insulation that provides a smooth interface for electrical stress relief. Manufacturing the semi-conducting material entails dispersing carbon black within a polymer matrix. Conventional conductor shields use furnace black, which is processed by controlled combustion of hydrocarbons. As a result, there is a high level of inorganic contaminants that accelerate water tree development in polyethylene-based cable insulation. In the late 1980's, super smooth/super clean (often called "supersmooth") conductor shield was introduced for MV cables in North America. The supersmooth conductor shield uses acetylene black manufactured from thermal decomposition of acetylene gas. This greatly improves the cleanliness of the compound. Further improvement in the manufacturing process provided a super smooth surface.

In 2014, it was estimated that that approximately 1/3 of the 2014 purchased length was supersmooth conductor shield designs [8], and a very small fraction (less than 1%) of the purchased length used conventional conductor shield.

However, in 2019, it was found utilities do not specify conductor shield type, thus implying either conventional or supersmooth designs, but more likely is supersmooth given the observed data trends from 2014.

Insulation Material

With premature failures of early installations of HMWPE and XLPE insulated cables from water treeing, TRXLPE and EPR have become the preferred alternatives for cable insulation in the USA. In this study, utility specifications were re-examined in 2019 to determine the acceptable material class, thereby extending the 10-year trend previously developed by Dudas to a 25-year trend.

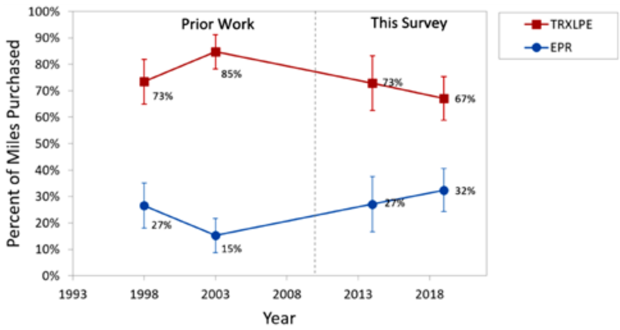

Fig. 2: A Twenty-Five Year Trend in Purchased Cable Length by Insulation Material

The prior narrative was based on the percentage of utilities specifying different insulation types, which is the method used in previous surveys by Dudas. Just because insulation materials can be specified on a system does not mean that insulation material was actually purchased/installed.

Fig. 2 shows the 2019 purchased length by insulation type, which considers the utility's size and captures which cable insulation will be installed. Nearly 2/3th of the reported purchased length per year (11,140 miles) was TRXLPE insulated. The remainder of the total purchased length (5,380 miles) was EPR insulated.

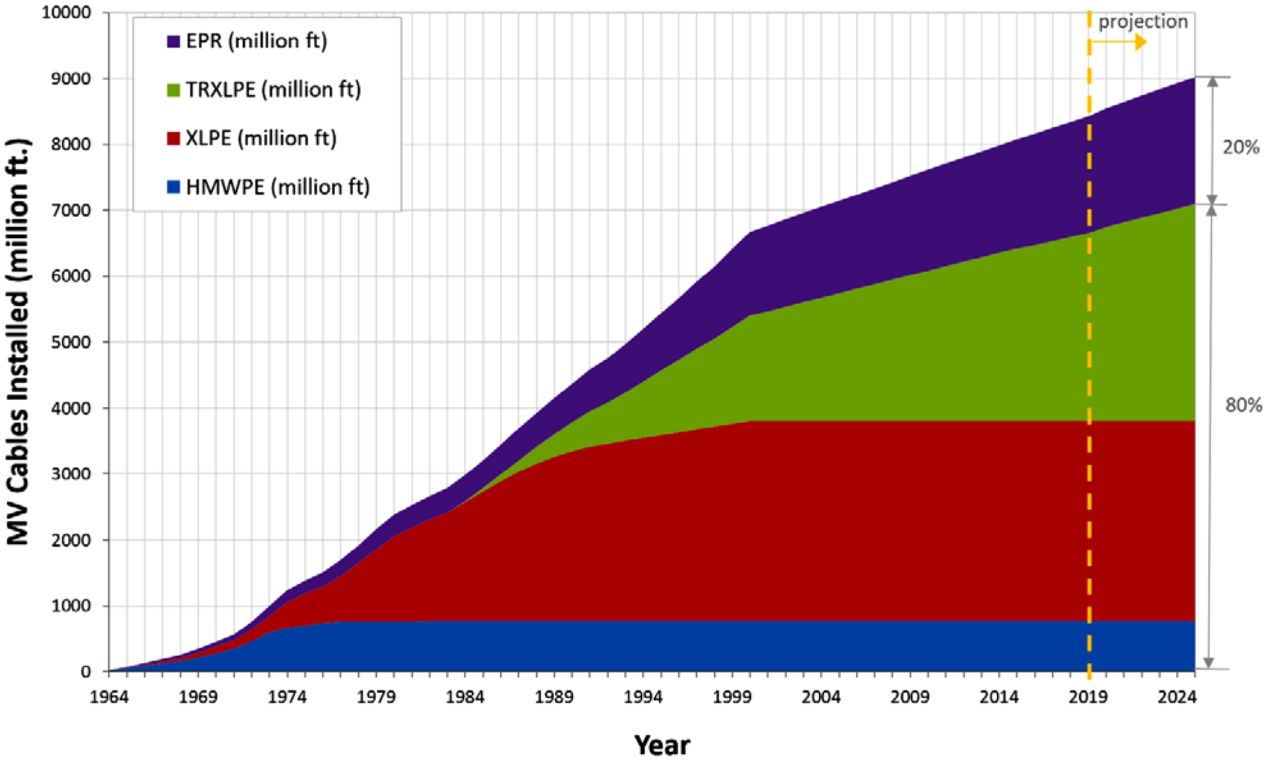

Fig. 3: Medium Voltage Cable Installation History in the United States Projected to 2024.

Fig. 2 also shows the 21-year trend of purchased length by insulation type. Purchased length data from the 1993 survey is not available to establish a comparable, earlier 15-year trend. A considerable increase in percent of purchased length occurred for EPR insulated cables from 2003 to 2019 (from 15% to 32%).

The demand share has since climbed back to 1998 levels. Using the 2019 and 2014 reported cable length as the average cable installation length per year for the past 15 years, the medium voltage cable installation history shown in Fig. 3 was extended based on this study and and the work undertaken by the authors in 2014. There was no adjustment made to the collated data to reflect missing utilities. Thus, the projected cumulative installed cable length by 2024 is a conservative estimate.

Insulation Thickness

Data from surveyed utilities were divided in five categories: reduced wall (<100% insulation), 100% insulation, 100-133% insulation, 133% insulation, and >133% insulation. The majority of the purchased length uses 100% insulation for 5 kV, 15 kV, and 25 kV class cables.

Extra caution was used for 35 kV class cables as enhanced insulation walls (>100% insulation) seems a preferred choice.

Few cables were reported as being purchased with reduced walls. A small percentage (<3%) reduced-wall insulation was purchased for 15 kV class cables and none for 5 kV, 25 kV or 35 kV classes.

The practice of utilities installing MV underground cables with reduced wall (<100% insulation), 100% insulation, and enhanced wall (>100% insulation) was extracted from prior work and extended with this study to develop a 25-year trend by voltage class. Some observations include:

- Small amounts of reduced wall cables were purchased for MV underground cables (15 kV, 25 kV, and 35 kV) in the past 20 years.
- Cables with 100% insulation are most preferred for 15 kV and 25 kV classes in the last 20 years. The same preference appeared in 35 kV cables in the 5-year range from 1998 to 2003; however, caution prevailed in the industry and the preference has changed back to 100% wall in the last 5 years.
- The demand shares of cables between 100% insulation and enhanced (thicker) wall varies among the voltage classes.
- Considering 15 kV cables, cable with 100% insulation comprises about 60-75% of the purchased length in the past 20 years. A gradual shift in preference from enhanced wall to 100% insulation has been a consistent trend as users gain more experience with 100% insulation cables.
- Considering 25 kV cables, there is a 10% decrease in the use of enhanced wall during the past 5 years indicating lesser caution by the utilities.
- Considering 35 kV cables, the practice has completely changed. There is a dramatic change (71% decrease) in the demand of MV underground cables with enhanced wall in the last 5 years (2014-2019).

Factors for Cable Selection

Utilities were asked to rate the importance of the factors listed in Fig. 4 (randomized order) based on their relative impact on the purchase decision-making process. The survey allowed each respondent to rate each factor from not important, somewhat important, moderately important, very important to the single most important factor. A compound score was calculated based on participants' responses.

Fig. 4 shows that expected life and experience at their utilities are the most important factors for decision-making, followed by compatibility with accessories, and cable manufacturer reputation. Cable cost is not one of the top five influencing factors. It is interesting to note that experience at a neighboring utility and industry presentations are at the bottom of the ranking list.

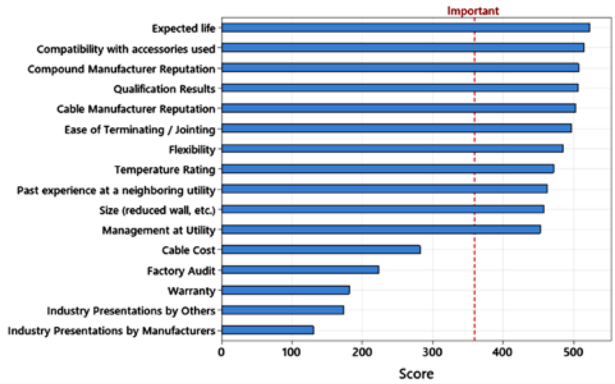

Fig. 4: Ranking of Important Factors for Cable Selection

Similar questions but fewer factors were surveyed in prior work by Dudas. The rankings in 2004 also indicated that expected life was the most important cable selection criteria; a priority that remains unchanged. This information is of increasing importance as many existing installed cables are 35+ years old and utilities want more insight into their expected service life. Unfortunately, there is no an existing testing program that can obtain such information. The closest effort in this area is the Accelerated Cable Life Test (ACLT).

Expert Opinion on Cable Generations and Expected Performance

Power cables have undergone significant changes since their inception, with advances in technology and materials driving improvements in design and performance. These changes have led to the development of different power cable generations over the years, each with its own unique characteristics and capabilities. The benchmarking conducted in this work also included questions related to medium voltage power cable generations, they included design and life expectancy. Answers were analyzed and results are presented in Table 1 and Fig. 5.

In Fig. 5, the horizontal lines represent the expert opinion for life expectancy by cable generation, the gray-dashed line the trend in life expectation. It can be noted that the increase of life expectancy by generation increases on average four (4) years per generation.

<table>
<tr><th>Gen.</th><th>Insulation</th><th>Semicons</th><th>Jacket</th><th>Barrier</th><th>Year Range</th><th>Avg. Expected Life [yrs.]</th></tr>
<tr><td>0</td><td>Paper Tape</td><td>Carbon Tape</td><td>Jacket</td><td>Extruded Lead</td><td>1900s~2005</td><td>64</td></tr>
<tr><td>1</td><td rowspan="2">Thermoplastic HMPWE</td><td>Graphite / Carbon Tape</td><td rowspan="5">None</td><td rowspan="7">None</td><td>1950s~1970s</td><td>19</td></tr>
<tr><td>2</td><td>Extruded Thermoplastic</td><td>1960s~1970s</td><td>24</td></tr>
<tr><td>3</td><td rowspan="4">XLPE or EPR</td><td>Graphite / Carbon Tape</td><td>1950s~1970s</td><td>31</td></tr>
<tr><td>4</td><td rowspan="3">Extruded Thermoplastic</td><td>1960s~1970s</td><td>29</td></tr>
<tr><td>5</td><td>1960s~1970s</td><td>32</td></tr>
<tr><td>6</td><td rowspan="4">Jacket</td><td>1960s~1970s</td><td>39</td></tr>
<tr><td>7</td><td rowspan="3">WTR XLPE or EPR</td><td rowspan="3">Extruded Thermoset (crosslinked)</td><td>1980s~1990s</td><td>54</td></tr>
<tr><td>8</td><td>Conductor Blocking</td><td>1980s~1990s</td><td>43</td></tr>
<tr><td>9</td><td>Blocking / Metal Barrier</td><td>1980s~Present</td><td>52</td></tr>
</table>

Table 1: Expert Opinion on Cable Generations Including Design and Life Expectancy

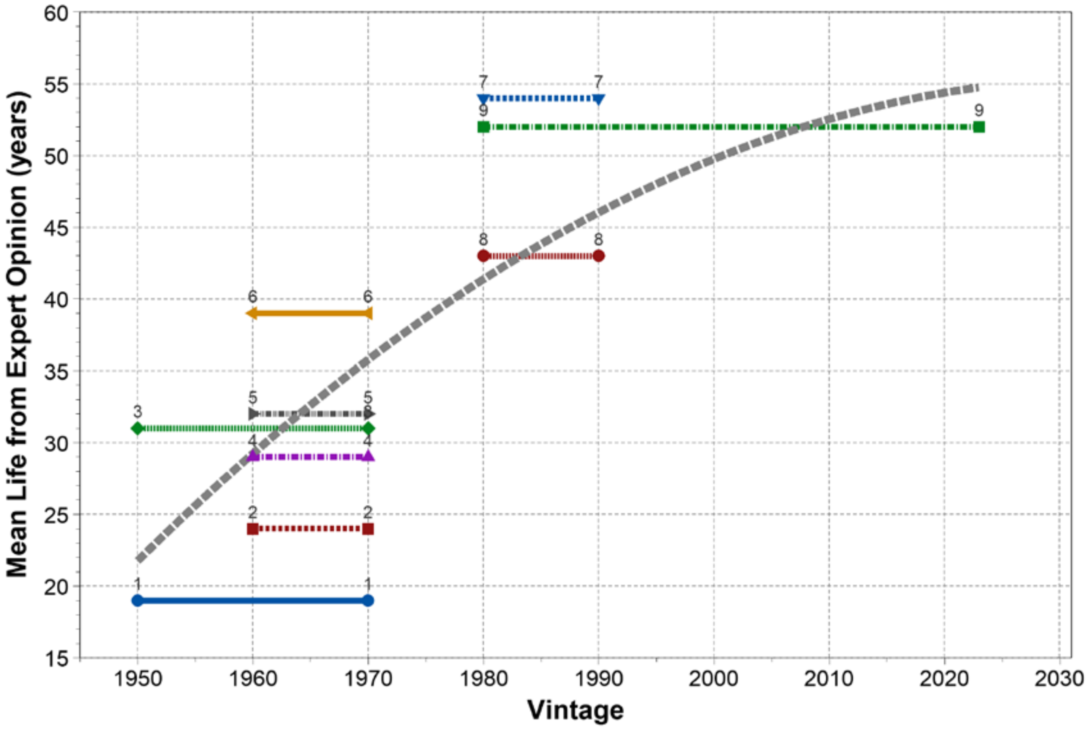

Fig. 5: Cable Generation vs. Expected Average Life (Life Expectancy) According to Expert Opinion

Accessories

Prior work by Dudas focused on medium voltage underground cables only. A number of issues on accessories were worth exploring. Thus, utilities were asked the types of joints, connectors, and terminations they purchased in 2019 and 2020. The topics in this section were included in the 2014 study and thus they have trends as that to review.

Connector Design

A 19% of the responding utilities indicated that they purchased crimp or compression connectors only in 2019; although, this percentage decreased to 1% from 2019 to 2020. In contrast, approximately four in five (4:5) of the responding utilities indicated that they purchased both crimp and shear bolt connectors in 2019; however, in this ratio increased to approximately nine in ten (9:10) utilities in 2020. None of the responding utilities purchased shear bolt connectors exclusively in 2019. The percentage, however, increased to 6% in 2020.

Joint Technology

Two thirds (2/3) of the responding utilities purchased heat shrink joints in the surveyed years (2019-2020). Other technologies included cold shrink and premold designs. Additionally, six in a hundred (6:100) of the responding utilities (6% in 2019 and 6% in 2020) purchased cold shrink or pre-molded joints only. The remainder utilities (94:100) purchased more than one type of joint design.

Termination Type

Considering dead front terminations, elbow terminations are purchased by more (marginally) utilities than T-bodies. This may be related to space limitations that affect the installation of T-bodies in some switchgear/transformer cabinets. There were also practical issues reported when pulling T-bodies off bushings during fieldwork. Approximately, 6% of the responding utilities purchased elbow terminations exclusively in the surveyed years.

Regarding live front terminations, cold shrink terminations are more widely used than other options such as heat shrink terminations, pre-molded terminations, or porcelain terminations. Thirty-eight percent (38%) of the responding utilities reported that they purchased cold shrink terminations exclusively in the surveyed years.

CONCLUSIONS

The focus of this study was medium voltage underground cable in 2019-2020, which makes up on average 20% to 30% of the primary distribution system for the surveyed utilities in the USA. This provides some context for the results presented in this report. The major conclusions are summarized for the cables and accessories purchased in 2019-2020 period as follows:

For MV Cable:

- Eight (8) in every 10 miles of cable purchased have an aluminum conductor.
- Eight (8) in every 10 miles of cable purchased have a water blocking feature.
- At least 3 in every 10 miles of cable purchased uses a supersmooth conductor screen.
- Seven (7) in every 10 miles of cable purchased use TRXLPE as the cable insulation material.
- Four (4) in every 10 miles of cable purchased are 15 kV voltage class.
- Eight (8) in every 10 miles of cable purchased use the 100% insulation level.
- Six (6) in every 10 miles of cable purchased have a concentric wire metallic shield.

For MV Accessories:

- At least 2 in 10 utilities purchase crimp connectors only.
- More utilities are switching from a single connector technology to allow both crimp and shear bolt connectors.
- Nine (9) in 10 utilities purchase more than one joint technology with cold shrink being the choice of most utilities.
- Four (4) in 10 utilities purchase terminations using cold shrink technology only.

The statistical margin of error (MoE) of this study was approximately 9% for a 95% confidence level. The MoE is estimated based on utility survey participation and considering approximately 3,000 utilities in the United States.

This study extended the 35-year medium voltage cable installation history to a 55-year view. This reflected market trends over the past 55 years and captured the installed miles of underground cables by insulation type.

This study also showed that the three most important factors for utilities when selecting a cable system were as follows:

1. Expected life.
2. Experience within the utility.
3. Accessory compatibility.

As society becomes increasingly reliant on electricity, power cable system design will continue to evolve, ensuring the safe and reliable transmission of electricity.

FUTURE WORK

As cable technology keeps evolving and maintenance practices change, NEETRAC plans to revisit the work presented here in the period 2025-2026 with the main goal of extend and analyse trends.

ACKNOWLEDGMENTS

The authors greatly acknowledge the support of NEETRAC members for allowing to share the work presented here.

REFERENCES

[1] I. A. Metwally, "The Evolution of Medium Voltage Power Cables," in IEEE Potentials, vol. 31, no. 3, pp. 20-25, May-June 2012.

[2] J. H. Dudas, “Technical trends in medium voltage URD cable specifications,” in IEEE Electrical Insulation Magazine, vol. 10, no. 2, pp. 7-16, March-April 1994.

[3] J. H. Dudas and J. R. Rodgers, “Underground cable technical trends for the largest rural electric co-ops,” 1998 Rural Electric Power Conference Presented at 42nd Annual Conference, 1998, pp. a3-1.

[4] J. H. Dudas and J. R. Rodgers, “Underground cable technical trends for the largest rural electric co-ops,” in IEEE Transactions on Industry Applications, vol. 35, no. 2, pp. 324-331, March-April 1999.

[5] J. H. Dudas and W. H. Cochran, “Technical advances in the underground medium-voltage cable specifications of the largest investor-owned utilities in the US,” in IEEE Electrical Insulation Magazine, vol. 15, no. 6, pp. 29-37, Nov.-Dec. 1999.

[6] J. H. Dudas and A. Necaise, “Advancements in underground cable material and design specifications of the largest rural electric co-ops,” Rural Electric Power Conference, 2004, 2004, pp. D3-1.

[7] J. H. Dudas and C. Fletcher, “Underground cable specification advances and installation practices of the largest investor-owned utilities,” in IEEE Electrical Insulation Magazine, vol. 21, no. 4, pp. 5-13, July-Aug. 2005.

[8] Shu. E, Hampton RN. (2019 June) Evolution of MV Extruded Cable Designs Used in the US from 1996 to 2014. Jicable19, E7.15.

[9] American Public Power Association, “2015-2016 Annual Directory & Statistical Report,” available at www.pulblicpower.org.

GLOSSARY

ACLT: Accelerated Cable Life Test
AEIC: The Association of Edison Illuminating Companies
Coops: Cooperatives
IOU: Investor Own Utilities