Lightning-Caused Distribution Outages

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Abstract—**Two rural distribution systems in Ontario, Canada were instrumented to study the relations between lightning events and power system disturbances. Strong time-of-day and time-of-year trends were found in the momentary operation history and component damage rates over four years of study. Implications for the entire Hydro-One Network design philosophy have been drawn from recent advances in the computation of induced overvoltages above lossy earth for overhead lines, inside lossy earth for cables and into two-layer soil for ground electrodes.**

Index Terms—**Cable, Distribution, Grounding Lightning, Induced Overvoltage, Insulation, Overhead Line**

I. INTRODUCTION

THE Hydro-One Distribution Network serves direct customers through a province-wide network of 44-kV or 27.6-kV Low-Voltage (LV) Feeders, leading to Distrubution Stations (DS) and Primary Feeders at a variety of lower voltage levels. Regulatory filings suggest that assets under management have a net book value of $Cdn 2.5 billion. The Hydro-One distribution business will be part of a group of regulated common carriers that supports Ontario's competitive electricity market.

The Hydro-One distribution system supplies about 960,000 retail customers, 100 small utilities (down from 200 in 1998) and more than 40 large industrial customers. It delivers power to these customers over assets consisting of approximately 119,100 km of lines (generally less than 50kV) and approximately 940 distributing stations. The oldest of these assets date back to the early 1900's. The distribution system is mainly a rural, radial system with limited backup supply from alternative circuits to primary supply circuits. As a consequence, component failures require immediate repair and/or replacement to restore service.

The replacement value of the distribution lines is listed as $1.1B, with an interest cost of roughly $100M per year or about $100 per direct customer. Faults on the distribution system cause the majority of direct customer interruptions. The distribution system also introduces a power loss of up to 6% in areas of lower customer density. The overall loss represents approximately another $100M per year to be transferred from customers to generation companies at today's uniform electricity rates.

South-west Ontario differs from other regions in Ontario because 27.6-kV three-phase LV Feeders are used for subtransmission. The rest of southern Ontario has 44-kV three-phase subtransmission. In north-western Ontario, the 115-kV transmission system serves as a direct supply to distribution stations (DS).

II. STUDIES OF DISTRIBUTION SYSTEM OUTAGES

A. *Ontario Hydro Reliability Study (1989-1992)*

Kinectrics carried out a long-term study of the operating reliability of distribution systems for the Canadian Electricity Association in the period 1989-1992. Data were collected over four years, using the using the Ontario Hydro **FA**ilure and **I**nterruption **R**eporting **S**ystem (FAIRS) that was a precursor to a modern Hydro-One Distribution Incident Reporting System (DIRS) and supporting database. Component failure statistics were tabulated and compared with observations of ground flash density in most of the Southwest Ontario operating regions. It took more than four years to complete the studies, which are summarised in reference [1].

Lightning flash data were collected in Southwest Ontario, using a network of first-generation gated wideband (LLP) receivers and advanced site-error processing [1]. At the same time, distribution system outage statistics were collected. A total of 40,000 records of equipment failure from the FAIRS results were analysed. The average system had 50 failures per 100 km of line each year, with lightning contributing roughly 15 of these failures.

Spot checks showed that the manual FAIRS reporting system identified half of the number of automatic faults. The FAIRS reports tended to ignore routine blown-fuse problems and to document failures of other components more reliably. Figure 1 shows that there was a strong time-of-day trend in the lightning outage failures in the FAIRS records.

Computerised systems were developed and applied to correlate the outage and lightning data automatically. Station Event

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Recorders (SER) provided 16 channels of voltage and current data using adaptive thresholds. In four years of study at two stations, 748 separate faults were diagnosed. More than 90% of these faults were found in SER records. The FAIRS system caught 9% of the faults missed by automatic records and only 1% of the faults undiagnosed. CIGRE Lightning Flash Counters (LFC) were used to provide local lightning data. The observed line tripout rates from lightning were 55 / 100 km-year and 29 / 100 km year in Drayton DS and Cedar Mills DS respectively. Three-quarters of these tripouts were correlated to the nearby lightning. The remainder labelled “Possible Lightning” in Figure 2, were nuisance fuse operations within 24 hours of storms.

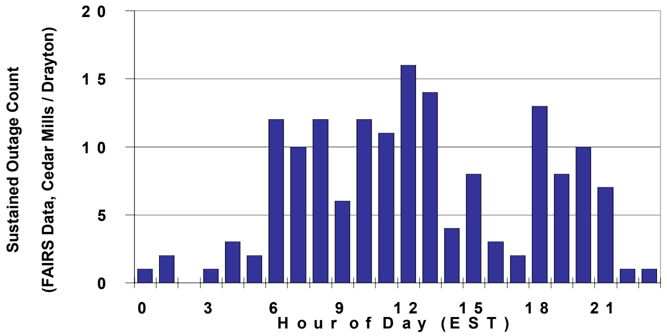

Figure 1: Time-of-Day Trend in Sustained Lightning Outages from manual records for Cedar Mills and Drayton (FAIRS data, 1989-1992)

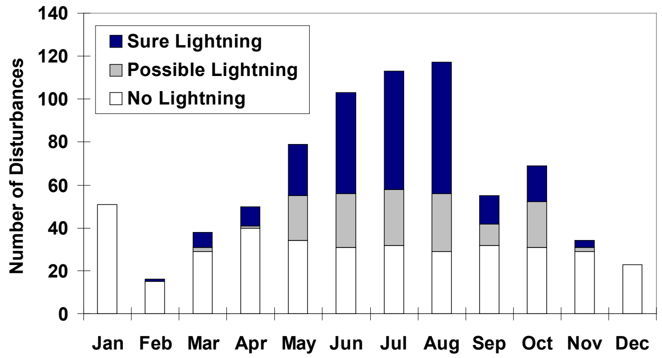

Figure 2 Time-of-Year Trend in Momentary Disturbances: Cedar Mills (1989-91) and Drayton DS (1990-91), ELDS Data [1]

Figures 2 and 3 show the strong observed relations between time-synchronised measurements of lightning activity and disturbances at the two stations. There was a steady background of about 30 disturbances per month, overlaid with as many as 90 additional disturbances in the peak lightning season of July and August.

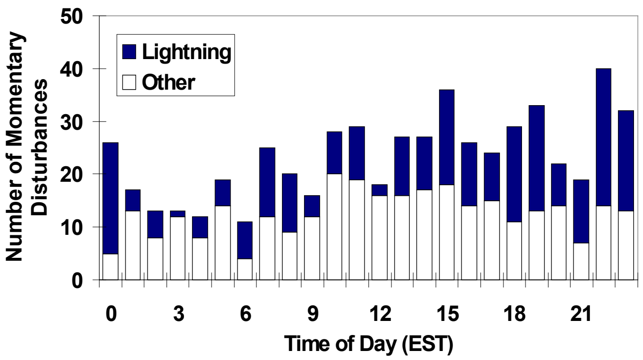

Figure 3 Time-of-Day Trend in Momentary Outages at Cedar Mills and Drayton DS (ELDS Data [1])

Figure 4 provides a more detailed breakdown of the observed causes of momentary disturbances.

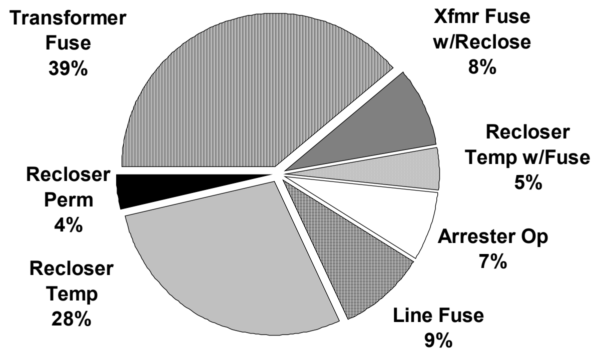

Figure 4: Observed Causes of Momentary Disturbances: Combined Cedar Mills and Drayton DS data from CEA 160 D 597 [1]

Case-by-case investigation to obtain the data in Figures 2-4 showed that most lightning tripouts occurred at weak-link structures where the insulation strength was compromised by ground connections, such as guy wires. Recent advice [2] that every grounded pole should have arresters was well supported in the case-by-case investigations.

III. SPECIFIC LIGHTNING MITIGATION ISSUES IN ONTARIO

A. Ground Flash Density Variation

Most measurements of ground flash density in Ontario show a gradient of activity. Peak levels of 2-3 flashes per km^2 per year are found in southwest Ontario, near Detroit. These levels fall off to less than 0.5 flashes per km^2 per year to the north and east of the province. It could be expected that the time-of-year trend, so strong in Figure 2 for the stations in southwest Ontario, would fall off in regions of low flash density. This was not found to be the case. Instead, the time-of-year trend remains strong in all regions. The interesting additional feature of the lightning environment in Ontario is that, wherever the lightning density is lower, the soil or rock resistivity is higher.

B. Grounding in the Resistivities of Ontario Soils

Ontario has a wide range of grounding conditions. In the farm areas west of Toronto, soil resistivity has been measured to be as low as 10 Ω-m. In eastern Ontario, parts of the Canadian Shield, a granite slab more than 1 km deep, presents a resistivity of 18,000 Ω-m. While a 3-m vertical rod will give a low resistance of 3 Ω in the southwest, the same rod would give more than 5000 Ω if it could be driven into the rock. The Hydro-One pole resistance standard is 25Ω.

Wenner probe surveys have been carried out at 52 TS throughout Ontario, and have been interpreted as two-layer soil models. This data set was used, along with models of grounding resistance in two-layer soil, to compute the effectiveness of different electrodes under lightning impulse conditions. Figure 5 shows that the target value of 25 Ω can be achieved with a single driven rod at 18 of 52 locations. Thus, a single driven rod is inadequate in 65% of the cases.

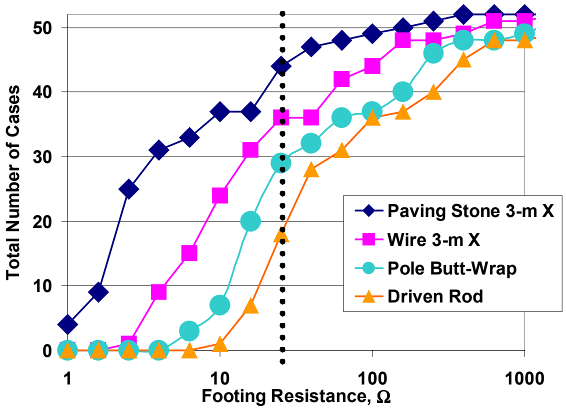

Figure 5 Resistance of Typical Pole-Bond Electrodes based on Two-Layer Soil Surveys for 52 Stations in Ontario

Within Hydro-One, there is a practice for some new construction of wrapping the base of the pole with wire, and leaving a short section at the bottom of the excavated hole prior to setting. This “butt-wrap” technique is more effective, with initial success in 29 of 52 cases, but is also more prone to damage. The standard “crowfoot” electrode, with four radial wires buried near the surface, is expensive to install and readily stolen but achieves 69% effectiveness. Other utilities [13-15] report similar problems. Development of lower-cost grounding electrodes, using electrically conductive concrete, has been identified as a Hydro-One development priority.

C. Insulation Levels for Induced Overvoltages

The main purpose of distribution insulation in lightning protection is to withstand induced overvoltages, rather than direct strokes. Generally, the number of induced flashovers can be reduced to a minimum if it is possible to maintain 300 kV BIL for ungrounded circuits or 230 kV BIL for typical single-phase feeders with grounded neutrals [2,12]. However, in areas where the ground resistivity is high, additional insulation is needed.

Figure 6 from [3] shows that, for the same design level of induced overvoltages per year, there should be higher insulation strength for the 1000 Ω-m case.

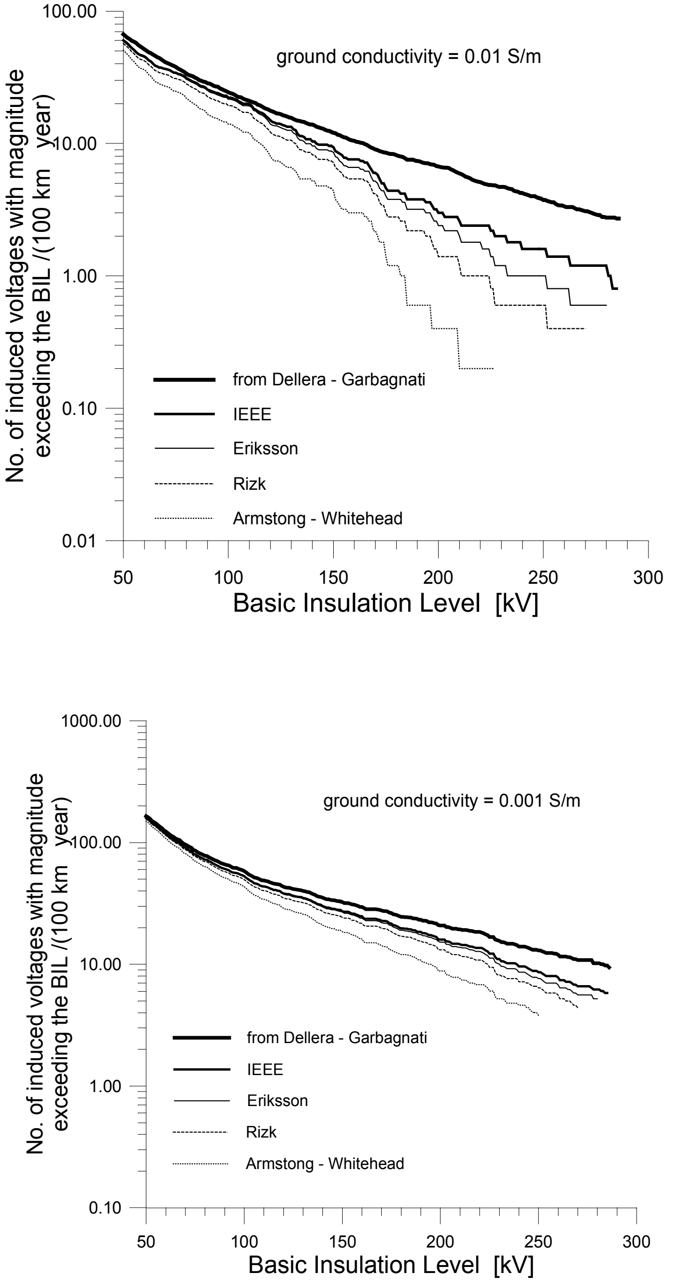

Figure 6 Calculated Number of Induced Overvoltages for 100-Ω-m and 1000 Ω-m Soils from Borghetti, Nucci and Paolone[3]

These two figures were used, along with traditional calculations for perfect ground, to infer the following recommendations:

- Lightning-induced overvoltage outages on LV Feeders should be mitigated to less than 0.1 outage per 100 km per year.

- Insulation levels should be maintained above 200 kV BIL at all structures, including weak-link guy poles.
- Additional insulation strength should be added to ensure low induced overvoltage tripout rates:

  - If no neutral is carried with a three-phase circuit, add 70 kV BIL
  - Where the soil resistivity >100 Ω-m, add 50 kV BIL
  - Where the rock resistivity >1000 Ω-m, add 150 kV BIL

Alternately, a minimum BIL of 420 kV could be used for all areas. This would require a total dry-arc distance of 0.75 m, or the equivalent length of about 1.8 m of wood pole or 1.2 m of seasoned crossarm.

The positive critical impulse flashover levels for various Canadian insulator classes are given in Table A.

Table A: Line Post Composite Insulator Requirements from (Canadian Purchase Specification) CEA LWIWG-02(96)

TYPE	LEAKAGE DISTANCE (mm)	DRY ARC DISTANCE (mm)	POSITIVE IMPULSE CRITICAL FLASHOVER
LP15	275	135	115 kV
LP25	420	195	150 kV
LP28M	585	235	180 kV
LP46	745	315	240 kV
LP46M	950	390	300 kV
LP69M	1450	510	350 kV

Present Hydro-One distribution standards call for conventional CEA DS46 or LP46M class for 44 kV systems on steel poles. A mix of insulation levels is presently listed at lower voltages on steel poles. As seen above, LP46M class insulators are recommended as a ***minimum*** for all line voltages on steel or concrete towers. The LP69M class is an appropriate choice in many regions. One difficulty with the selection of LP69M insulators, compared to all others in Table 4.2, is that the base threading is 7/8" rather than ¾".

Hydro-One distribution standards for primary one-phase wood pole lines specify an LP-28P insulator for at any voltage. This nonceramic insulator, with its 180 kV BIL, appears in series with a minimum of 0.9 m of wood pole. The combined strength is approximately $(180\ \mathrm{kV}^3 + 220\ \mathrm{kV}^3)^{1/3}$ or 250 kV [5]. This could be increased to 420 kV BIL by the following combinations:

Wood length of 1.7 m and LP28M insulator
Wood length of 1.6 m and LP46 insulator
Wood length of 1.5 m and LP46M insulator
Wood length of 1.3 m and LP69M insulator

The option of **1.7-m wood** length is recommended because it will also satisfy the criterion [6, p95] for good power-system arc quenching on the common 16.6-kV single-phase lateral circuits.

Subtransmission circuits at 44 kV list LP-46 insulators along with a minimum wood path of only 0.25 m from the central pole-top bracket base to the stand-off bracket. Typically, there are no neutral or ground connections, so the entire pole provides insulation strength. Phase-to-phase flashover levels [6] suggest that this wood length is too short to contribute to either flashover strength or to power-arc quenching. However, there is not much phase-to-phase impulse voltage under induced overvoltage conditions because the same horizontal and vertical electric fields illuminate all three phases. A vertical wood-pole configuration with 1.3 m phase separation would give a 50% success rate in quenching phase-to-phase power arcs after flashover from direct strokes, and 2.5-m vertical separation would improve the success to 70%. The LV Feeder insulation strength should be maintained by using 450-kV BIL class insulators (with minimum leakage distance) in series with all guy wires.

The performance that can be achieved with increased insulation can be illustrated by checking results from higher-voltage feeders. Michaud [7] reported 17.5 lightning faults per 100 km per year on the existing French 63-kV and 90-kV networks. These lines are "partially shielded" near substations and insulated at 280 to 400 kV BIL in an area with ground flash density roughly equal to Ontario. Michaud further estimates that the performance would improve to 7 faults per 100 km if the BIL was increased to 580 kV.

D. Underground Cable Protection

Underground cable lightning protection is often ignored as trivial, compared to other long-term problems such as moisture ingress or neutral corrosion. However, even in typical soil and especially when resistivity exceeds 1000 Ω-m, the induced overvoltage environment around cables can be nearly as severe as the overhead-line conditions.

Underground rule-of-thumb models for induced overvoltages suggest that an effective conductor height of 1 m over perfect ground matches damage frequencies. The local ground flash density and the insulation levels on open-wire connections to remote motors can then be interpreted in forensic analysis using the Rusck model [8]. These investigations are normally carried out to support insurance claims after indirect lightning has failed a large motor.

Cooray [9] gives a more rigorous set of calculations that refine the induced overvotlage environment. For a range of soil resistivity and distances, the *vertical* electric field from nearby lightning falls by a factor of 60:1, as would be expected from a small angle of incidence and the high EM wave reflection coefficient. However, the *horizontal* electric field (which does much of the work) changes less than 20% for 2-m depth of burial, compared to the value at the surface or 10 m above ground. The azimuthal magnetic field shows similar behaviour. The duration of the inducing potentials is relatively short for good soil. This benefit to insulation disappears for resistivity above 500 Ω-m as the "relaxation time" of the soil increases above 1 μs.

A numerical example [9] for a buried wire at a depth of 1 m, 1 km away from a 13-kA subsequent stroke in 200 Ω-m soil results in a horizontal E-field of $E_z = 35$ V/m. Using a simple transfer impedance model [10] and neglecting the radial magnetic field term, the induced current in a buried wire from remote lightning will be $I = E_z / j\omega(1\ \mu\text{H/m}) = 55$ A (about 25 kV peak into the wire surge impedance). The induced overvoltage would increase as lightning moves closer. For a 10 km buried wire in Ontario (Ng=1), there will be two subsequent strokes within 100 m every year. One of these strokes would induce more than 300 kV in the open wire relative to remote ground.

A cable with 100 kV BIL will be able to withstand about 150 kV for the short-duration surges produced by the horizontal E-field. More important, if fitted, is the electrostatic shielding provided by a concentric neutral. This provides a reduction in surge voltage proportional to $e^{-d/\delta}$, where d is the neutral thickness and δ is the traditional skin depth (about 200 μm for copper at lightning frequencies). These considerations, along with ability to withstand direct lightning arc activity, should affect the choice of neutral material and coverage. For example, Valli et.al [11] recommend a reduced-neutral XLPE cable design. Their concept would be appropriate for British Columbia, where there is low lightning activity, but a 127-μm copper tape overlay would not provide adequate EM shielding in parts of Ontario. It is not feasible to upgrade the middle of a cable by fitting surge arresters because this generally introduces additional components, fittings and accessories and their related workmanship and reliability problems. For these reasons, the underground cable concentric neutral configuration be co-ordinated with the lightning withstand strength of the cable, typically giving a neutral thickness greater than one or two skin depths at 100 kHz.

The interface between the cable neutral and the ground is important at interfaces between water and rock. Typically, in Ontario, the water resistivity is 80 to 140 Ω-m and this can be two orders of magnitude lower than the underlying rock. In cases where lightning strokes terminate on rock near underwater cables, the cable neutral can serve as a focal point for conducting most of the current into the water. A low-impedance connection between the neutral and the local ground should provide sufficient surface area to prevent overheating or arcing.

IV. CONCLUSION

In spite of its relatively low lightning ground flash density, Ontario presents many challenges to the provision of disturbance-free electric power through its distribution system.

Measurements at instrumented stations, followed up with detailed forensic investigations at failure sites, have quantified the main origins and failure mechanisms of disturbances. The studies at two different DS over four years also reinforced the point that most of these failures occur at structures where the insulation strength has been weakened.

In its areas of high soil resistivity, Hydro-One has identified a need to improve the effectiveness of its pole bond and other ground electrodes. In these same areas, recent computational work now suggests that insulation levels in excess of 400 kV BIL may be appropriate, where 200 kV might be acceptable over perfectly-conducting ground.

A third point, identified in the recent literature, is that buried cables in poorly-conducting ground may also be susceptible to induced overvoltages. This could be a concern for cables that use concentric neutral tape layers that are thinner than the skin depth at 100 kHz.

V. ACKNOWLEDGMENT

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VII. BIOGRAPHIES

William A. Chisholm (M’81, SM’89) was born in New York in 1955. He graduated from the University of Toronto in Engineering Science (1977), M.Eng (1979) and PhD (1983) in Electrical Engineering from the University of Waterloo. Chisholm joined the Ontario Hydro Research Division (now Kinectrics) in 1977. He has completed many research projects in transmission and distribution system reliability, leading to more than twenty IEEE and CIGRE publications. His special interests are lightning protection, overhead conductor ampacity and electrical performance of insulators under icing conditions. He has recently been promoted to Senior Project Manger at Kinectrics. He is Chairman of the IEEE Lightning and Insulator Subcommittee, former editor of IEEE Standard 1243 and a Registered Professional Engineer in the Province of Ontario.

Stephen L. Cress was born in Toronto in 1952. He graduated from the University of Toronto in Electrical Engineering (1976) and worked for Federal Pioneer. He joined Ontario Hydro Research Division (now Kinectrics) in 1978. During his time at Kinectrics, Mr. Cress has conducted major investigations for North American distribution utilities associated with distribution systems and equipment including Overcurrent Protection (fuses, reclosers, sectionalizers, breakers, relays, electronic fuses, network protectors); Testing (high voltage fuses, switchgear); Power Transformers (loading. sizing, losses and loss evaluation, life assessment and extension); Planning (capital efficiency and asset utilization, system loss evaluation and mitigation); Modeling (load flows, loss analysis, protection coordination, ferroresonance, software development); Failure Analysis (switchgear, fuses, transformers, capacitors, cables, arc radiation) and Utilization (Internet SCADA systems).

Mr. Cress specializes in the area of overcurrent protection and is the holder of a US patent on high voltage current limiting fuses. He wrote the CEA reference book “Application Guide for Distribution Fuses”. His work led to the development of the TRANSIZE (transformer loss evaluation) and ARCPRO computer program (North American standard for conducting the US OSHA mandated hazard assessment of clothing for workers who may be exposed to electric arcs.)

Mr. Cress has made numerous presentations at CEA and MEA Conferences and has published papers with IEEE, CIRED, and INTER-RAM. Mr. Cress is the Chairman of the CSA and IEC National Committees dealing with high voltage fuses. He was a Canadian Specialist on the IEC TC32 working group dealing with high voltage fuses. He is a Registered Professional Engineer in the Province of Ontario.

Janusz Polak (M88) graduated from the University of Mining and Metallurgy, Krakow , Poland with M. Sc degree in Electrical Engineering. He joined Ontario Hydro in 1988 and was involved in various aspects of Transmission and Distribution station design: Arrangement, Basic Layout, Protection Control and Metering. Currently he is responsible for distribution system standards in Hydro One. He represents Hydro One on CSA and IEEE committees. He is a member of IEEE and a Registered Professional Engineer in the province of Ontario