SUSTAINABILITY OF AN ELECTRIC ARC FLASH AT A VOLTAGE OF 240 VAC AND 150 VDC

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Kirk Gray P.Eng
Member, IEEE & OIQ
Hydro-Québec
Montréal, QC Canada
gray.kirk@hydro.qc.ca

S. Robert P.Eng
Member, OIQ
Hydro-Québec
Montréal, QC Canada
robert.simon@hydro.qc.ca

Rémi Hallé, P. Eng
Member, IEEE & OIQ
BBA Inc.
Mont-St-Hilaire, QC Canada
remi.halle@bba.ca

Abstract —The purpose of this paper is to present arc flash laboratory results related to the occurrence of an electric arc flash and the protection offered to workers during arc flash event. The goal was to carry out laboratory tests in order to evaluate the sustainability of an electric arc flash at a single phase voltage of 240 Vac, and the adequacy of the choice of the formula for evaluating the incident energy at 150 Vdc compared to the values obtained in the laboratory. For alternating current, there is a discrepancy according to the applicable standard for the same task. This discrepancy results in the application of different safety measures. Preliminary research tends to support the thesis of a non-sustainability of the electric arc flash at 240 Vac, whereas the use of the formula employed for the direct current would be far too conservative compared to laboratory tests. Following confirmation of the preliminary results, it would be possible to review the protection required during high-risk dc tasks and to rule on the dangerousness of several activities. Doing so could eliminate the need to wear PPE, or reduce the necessary protection associated with risky procedures.

Index Terms — Arc flash, incident energy, personal protective equipment.

I. INTRODUCTION

Utility safety standards require workers to be protected from arc flash hazards when work is performed in an energized equipment. The hazard should be identified on the panel with the level of incident energy at a working distance. Workers must wear personal protective equipment (PPE) rated at least to the level associated with the label on the panel when high risk task requires it.

The utility has several levels of low voltage system voltages, as 125 Vdc and 240 Vac, and it was uncertain at what voltage level the arc can be sustained and able to produce incident energy over 1.2 cal/cm^2. Once that data is known, it facilitates the process of determining where and when to perform incident energy analysis in order to optimize workers' safety.

Also included in the paper is a comparison of the incident energy levels from test results against results from different kinds of calculation methods.

II. TEST OBJECTIVES

A first objective was to determine if an alternating single phase current arc flash at 240 Vac can be sustained and able to generate an incident energy above 1.2 cal/cm^2 at a typical working distance on equipment installed within the scope of tasks carried out by the utility.

If the electric arc is maintained during the tests at 240 Vac, and developed more than 1.2 cal/cm², it would be important to know the parameters necessary to maintain this arc according to the established criteria.

In addition, the authors wants to provide more results following the 2018 tests concerning dc arc maintainability for voltage levels of 100 ≤ Vdc ≤ 500 [1]. More specifically, it is important to determine if at the voltage level of 150 Vdc, wearing arc flash PPE rated 8 cal/cm² would be sufficient for adequate protection against an electric arc. The objective is to establish the voltage level at 150 Vdc to cover the organization's voltage levels for automation protection systems at 129 Vdc nominal but varying in the range 105 ≤ Vdc ≤ 140.

During the tests of the voltage levels mentioned above, measurements will also be made concerning the heat release during the initiation of an arc flash. These measurements will make it possible to validate the theoretical results during the execution of the incident energy analysis. To measure the incident energy, calorimeters were set up at distances of 18 and 15 inches from the arc initiation location. For testing and analysis purposes, any arc with incident energy over 1.2 cal/cm^2 would be considered as a sustainable arc that presents an arc flash hazard. The tests were limited to creating an arcing fault with in-line vertical copper electrodes and parallel electrodes, using these two possible configurations: an arc in a box and an arc in open air. The test conditions recreated in the lab do not represent all possible types of arcing faults at facility installations. The objective was to provide test results to assist the utility in its arc flash risk assessment of low voltage dc and ac installations.

III. TEST CIRCUIT

All work was performed at a high current test laboratory in Toronto, Ontario. The selection of the voltage and fault current for the laboratory tests were based on systems voltage and fault current found in real-world facilities. The tests were carried out in a controlled environment similar to that of the organization's facilities. The objective, for these voltage levels, 150 Vdc and 240 Vac, was to determine the conditions where the arc is maintained and produce an incident energy of more than 1.2 cal/cm² at a working distance. The tests were divided in two phases and each different scenario.

PHASE 1 : 150 Vdc

For this phase, the test voltage was established at 145 Vdc. The parameters of this test were the following:

- 15 vertical in line electrodes attempts.
- 10 parallel electrodes attempts.
- A maximum bolted short-circuit current capacity of 17 kA
- The space between the electrodes between 6 to 12 mm.
- Calorimeters reading distance was established at the working distance of 18 inches (457 mm). Two sensors are located at the working distance.
- Type of arc initiation electrode material: copper rod with flat ends (25 mm in diameter).
- Arc start wire material type was 20 AWG copper.
- A maximum arc current injection time of 2 seconds.

PHASE 2 : 240 Vac Single Phase

For this phase, the test voltage was established at 235 and 246 Vac single phase that are within operational limits of a 240 Vac nominal network. The parameters of this test were the following:

- A maximum bolted short-circuit current capacity of 10 and 15 kA that are in normal usual short capacity of 240 Vac equipment (rated typically 10 kA or 22 kA)
- The space between the electrodes was 5 and 6 mm.
- Calorimeters reading distance was established at the working distance of 18 and 15 inches (457 and 381 mm).
- Type of arc initiation electrode material: copper rod with flat ends (25 mm in diameter).
- Arc start wire material type was 20 AWG copper.
- A maximum arc current injection time of 2 seconds.

The tests were conducted with circuits having a maximum bolted fault current of 17 kA, a maximum and fixed value within the prescribed range of the source available in the laboratory that allowed it. The arcing fault currents were from 2 kA to 12 kA for a arcing voltage ranged from 34 to 135 Vdc. This paper provides some details of the test conditions and measured parameters.

The test set-up and electrode-supporting apparatus provided by the testing facility was placed in the test cell as shown in Figure 1 (vertical in-line) and Figure 2 (horizontal parallel).

For each phase, two scenarios were evaluated.

The first scenario is the case where an arc occurs inside an enclosure, having the arc energy directed outwards toward the calorimeters. This was represented by a ceramic box with a curved back and sides as to provide the highest incident energy transfer to the surface placed in front of the box. Testing is performed in accordance with IEC 61482-1-2 [2].

The second scenario is the case where an arc is generated without directing or focusing the energy towards the calorimeters. The energy may be dispersed 360° around the plane of the arc gap. In this case, the same electrode placement and gap is used, but no enclosure. These two cases serve to represent the range of incident energy that is expected to be observed given the same condition of arcing fault. It is believed that metal enclosures such as disconnect switches and cabinets would not be as efficient as the ceramic box at focusing the thermal energy and would result in incident energy between these two scenarios.

The 25 mm diameter copper electrodes entering from the top and bottom were adjusted to be mid-way into the box or the open area. The gap was adjusted before each test and bridged by a 20 AWG copper wire. Once the fault current was applied, the fine gauge wire melted within 1 millisecond and the arc was established. The circuit protection was set to 2 seconds for all tests. In many cases, the arc blew out and was not sustained for the full duration of the test.

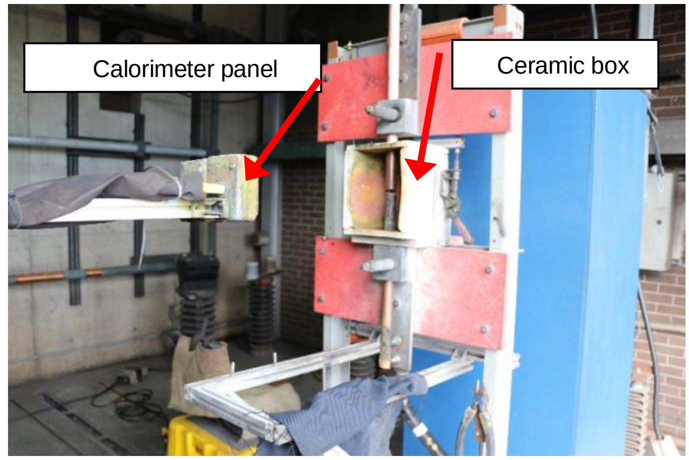

Figure 1 View of the vertical in-line electrodes with box

Figure 2 View of the horizontal parallel electrodes, no box

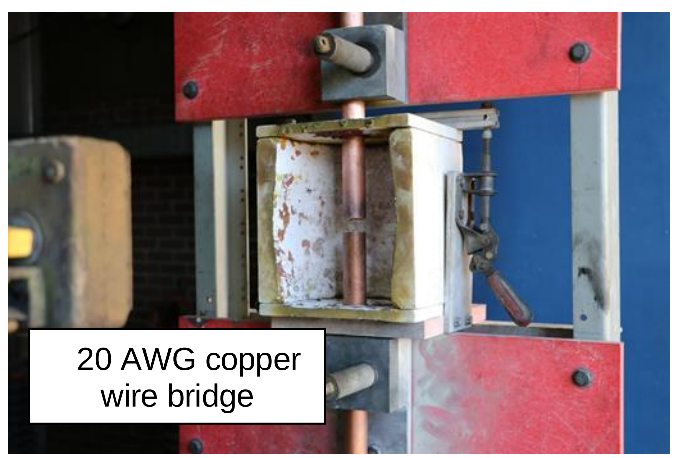

Figure 3 View of the copper electrodes and bridge

After each test, the electrodes were removed, the molten tip was cut off and the tips were dressed to original condition. A close-up of the electrodes with the bridge wire is shown in Figure 3.

IV. TEST RESULTS

A total of 55 tests were performed. The analyze was performed on 23 test at 150 Vdc and 21 at 240 Vac. Tests were repeated a minimum of 3 times at each condition to provide additional confidence and stability to the final outcome. Before the beginning of the tests series, a bolted fault test was performed to determine the actual circuit impedance. In low dc voltage circuits, the measured arc current can be significantly less than the bolted fault due to the resistance of the arc and the voltage drop across the arc. A summary of the tests is shown in Tables I and II. Only test results with incident energy above 1.2 cal/cm² were detailed in these tables. The results below 1.2 cal/cm² were grouped when more than one and only the maximum value of the tests was shown. The incident energy shown in tables is the average value of the measurements of the two sensors at the specified working distance. For Phase 1, at 150 Vdc, the maximum difference between sensor was lower than 0.2 cal/cm². For Phase 2, at 240 Vac, the difference was below 0.2 cal/cm² for results below 3 cal/cm². For higher results above 10 cal/cm², the worst difference between sensor was 2.4 cal/cm².

TABLE I
SUMMARY OF PHASE 1 ARC RESULTS AT 150 VDC SOURCE

Test Number	Bolted Fault (kA)	Elect. Orient.	With Box	Test Voltage (V)	Electrode Gap Initial (mm)	Electrode Gap Final (mm)	Arc Current (A)	Arc Voltage (V)	Arc Duration (s)	Working Distance (mm)	Incident Energy (cal/cm²)
2287	17	In-Line	Yes	145	6	21	7.75	77	0.327	457	0.81
2088						22	7.70	76	0.415		1.22
2089						23	7.40	80	0.476		1.20
2090						25	7.15	81	0.463		1.29
2091						26	7.38	79	0.552		1.40
2 Tests	17	In-Line	No	145	6	< 25	< 7.52	< 86	< 0.443	457	< 0.47
5 Tests	17	In-Line	Yes	145	12	< 26	< 6.29	< 122	< 0.410	457	< 0.92
2 Tests	17	In-Line	No	145	12	< 21	< 5.28	< 103	< 0.27	457	< 0.32
5 Tests	17	Parallel	No	145	8	N/A	< 5.5	< 110	< 0.016	457	< 0.1
4 Tests	5.7	Parallel	No	141	8	N/A	< 4.1	< 53	< 0.034	457	< 0.1

TABLE II
SUMMARY OF PHASE 2 ARC RESULTS AT 240 VAC SINGLE PHASE SOURCE

Test Number	Bolted Fault I_{bf} (kA)	Elect. Orient.	With Box	Test Voltage (V)	Electrode Gap Initial (mm)	Electrode Gap Final (mm)	Arc Current I_a (A)	Arc Voltage (V)	Arc Duration t (s)	Working Distance (WD) (mm)	Incident Energy E_i (cal/cm²)
2120	10.7	In-Line	Yes	235	6	35	8.5	91	0.76	457	3.05
2121						40	8.5	93	0.76		2.70
2122						50	8.2	102	1.2		4.95
2123	10.7	In-Line	Yes	235	5	20	8.9	75	0.24	381	1.30
2124						40	8.3	94	0.86		5.95
2125						20	8.8	80	0.3		1.30
2126	10.7	In-Line	No	235	5	35	7.7	125	1.00	381	2.77
2127						35	8.1	102	0.87		2.75
2128						33	8.4	94	0.82		2.20
2 Tests	10.7	In-Line	No	235	6	< 25	< 8.6	< 89	< 0.55	457	< 0.9
2131						33	8.2	100	0.74		1.30
3 Tests	10.7	Parallel	No	235	5	N/A	< 11.5	< 135	< 0.009	457	< 0.18
3 Tests	10.7	Parallel	Yes	235	5	N/A	< 11.2	< 134	< 0.01	457	< 0.21
2133	15	In-Line	Yes	246	5	46	11.5	112	0.8	381	13.00
2134						58	11.5	113	0.87		12.60
2136						48	10.6	122	0.5		7.15

Notes : For test 2126 the current stopped for a duration of 0.098 s and then restrike and continue for another 0.202 s

V. TEST ANALYSIS AND OBSERVATIONS

A. Analysis of the 150 Vdc test results

The summary results at 150 Vdc can be found in Table I.

At 145 Vdc, it was possible to initiate an electric arc generating more than 1.2 cal/cm² at 457 mm (18") with the vertical in-line configuration and an initial inter-electrode spacing of 6 mm (0.25"). The arc extinguished itself after 300 to 500 ms with a final inter-electrode spacing of about 25 mm (1"). However, the measured incident energy at 457 mm (18") never goes above 1.4 cal/cm². The arcing current were between 30 to 45 % of the bolted fault current.

With a initial gap of 12 mm an arc was able to sustained but not sufficient long to reach the threshold of 1.2 cal/cm².

After 9 tests, it was not possible to initiate an arc with a parallel electrode spacing of 8 mm. The arc was blow out extremely fast and did not sustain enough long (< 17 ms) to even dissipate an incident energy above 0.1 cal/cm².

These results are in accordance with similar results obtained in 2018 [1]. With similar inputs parameters, similar results are obtained. In these previous tests, the maximum incident energy found at 144 Vdc was 1.7 cal/cm² at 450 mm for an initial gap of 6 mm with a box.

With the vertical in-line configuration, all tests stopped by themselves when the electrode gap reached 20 to 25 mm. The burn back on the electrodes for some of the tests was significant. The electrode burn back depends on the material and the size of the electrode (bus bar).

B. Analysis of the 240 Vac single phase test results

The summary results at 240 Vac single phase can be found in Table II.

At 235 Vac, as for 145 Vdc, it was also not possible to initiate an arc with a parallel electrode configuration even if only spaced of 5 mm. The arc was blew out extremely fast and was not enough long to reach 0.1 cal/cm² at 457 mm (18").

At 235 Vac, with an available bolted fault of 10 kA, it was possible with the in-line configuration to initiate an electric arc and sustained it during 0.24 to 1.2 seconds (14 to 72 cycles). The incident energy was able to reach 6 cal/cm² at 457 mm (18"). At 235 V, the final gap, starting at 5 or 6 mm, were between 20 to 50 mm.

At around 245 Vac with 15 kA bolted fault at a working distance of 381 mm (15") and the in-line configuration, it was possible to initiate an arc of more than 8 cal/cm² with an initial inter-electrode spacing of 5 mm. An incident energy value of 13 cal/cm² at 381 mm (15") was event reached. The arc self-extinguished after less than 1 second (60 cycles) with a final inter-electrode spacing of about 50 mm.

With the in-line configuration with small gap, the conditions are sufficient to sustain an arc at 240 Vac and allow the restrike after each zero crossing of the sin wave of alternating current. The incident energy is also able to reach value above 1.2 cal/cm² at 381 or 457 mm (15" or 18"). During one test (2126), the electric arc stopped during 98 ms (5.9 cycles) and restriked the electric arc by itself and continue arcing for another 200 ms.

VI. CALCULATION METHODS COMPARAISON

A. Calculation methods

To perform arc flash risk assessment for activities on electrical equipment it is important to evaluate the incident energy in case of an arc flash to have an idea of the possible severity and to select arc rated PPE when required. The obtained results were compared to calculation results from different existing methods.

Different methods currently exist to evaluate the incident energy in case of an arc flash on DC systems. Using the tests parameters, the three DC methods were compared to the obtained results to evaluate which of these methods are closer to the results.

The first and most knows is the Maximum Power method. This method doesn't take into account of lot of parameters as the electrode gap or orientation.

A second method is the Stokes and Oppenlander (S&O) method. A third method is Paukert. These two methods take into account the gap between electrodes.

For the three DC methods, no multiplication or adjustment factors were applied to take into account the arc in a box . The value given by these methods seems to be already conservative. The goal was to compare them as much as possible with same base parameters.

For single phase AC, there are not currently a lot of methods available. IEEE 1584-2018 [2] does not cover the single-phase equipment. The use of the three phases systems equation of this method with single phase parameters is expected to be conservative. For enclosed tests, the electrode orientation vertical in a box (VCB) was used because it normally leads to lower results and may allow to be less conservative. The typical guide enclosure dimension 356 x 305 x 203 mm was used. For open air tests, the electrode orientation vertical in open air (VOA) was used.

A second calculation method was used for the single phase. It is included in a heat flux calculation software. This software included an alternative single phase method. The calculation is based on voltage, bolted fault current, X/R ratio, electrode material, frequency and gap. The X/R ratio used was 2 for tests with bolted fault of 10 kA and 3 for bolted fault of 15 kA. A gap of 25.4 mm (1") was used with this method instead of exact the gap of 6 mm or the tests because it is the minimum allowed by this method. When a box was used, the parameter "enclosed" of this software was used.

All AC or DC calculation with above methods were performed using available commercial software's.

B. Comparison of calculation and tests results analysis

The test and calculation results comparison are found in Table III for 150 Vdc and Table IV for 240 Vac.

For the 150 Vdc, the three analyzed calculation ends to similar results but remains 2 to 5 times higher than test results.

It must be noted that for the DC calculation no multiplication factors or were used because the open air results of these method are already many time higher than tests results at 150 Vdc. For example, Maximum Power method recommend a multiplying factor of 3 for enclosed equipment which lead to extremely conservative results for the analyzed results.

It is important to emphasize that the incident energy levels measured during the tests are all lower than the theoretical DC levels obtained with the existing method formulas even before applying enclose multiplication factor. This is an indication that PPE based on the existing formulas are conservative, but adequately protect workers from the incident energy released from an arc flash. This comparison is for 150 Vdc range with small gaps and might not be the same at other voltage levels.

For the 240 Vac results, the results with IEEE 1584-2018 three phase formulas but used with single phase parameters gives results between 0.9 to 3 times the test results. With IEEE 1584-2018, for enclosed equipment, VCB electrode configuration was used to have less conservative incident energy values. The method with the heat flux software gives results between 0.6 to 1.2 time the test results.

TABLE III
COMPARAISON OF 150 VDC TEST RESULTS WITH CALCULATION METHODS

Test Number	Test results								Maximum Power		S&O		Paukert	
	V (Vdc)	I_{bf} (kA)	I_a (kA)	With Box	Gap (mm)	t (s)	WD (mm)	E_i (cal/cm²)	I_a (kA)	E_i (cal/cm²)	I_a (kA)	E_i (cal/cm²)	I_a (kA)	E_i (cal/cm²)
2091	145	17	7.38	Yes	6	0.552	457	1.40	7.61	2.92	8.04	2.76	5.93	2.63
2100	145	17	6.90	No	6	0.443	457	0.47	7.61	2.34	8.04	2.21	5.93	2.11
2296	145	17	6.16	Yes	12	0.410	457	0.92	7.61	2.17	7.16	2.05	7.68	2.06
2097	145	17	5.28	No	12	0.270	457	0.32	7.61	1.43	7.16	1.35	7.68	1.35

TABLE VI
COMPARAISON OF 240 VAC SINGLE PHASE TEST RESULTS WITH CALCULATION METHODS

Test Number	Test results								IEEE 1584 2018		Heat Flux Software	
	V (Vac)	I_{bf} (kA)	I_a (kA)	With Box	Gap (mm)	t (s)	WD (mm)	E_i (cal/cm²)	I_a (kA)	E_i (cal/cm²)	I_a (kA)	E_i (cal/cm²)
2122	235	10.7	8.2	Yes	6	1.2	457	4.95	7.68	9.08	6.41	4.7
2124	235	10.7	8.3	Yes	5	0.86	381	5.95	8.16	8.76	6.41	4.9
2127	235	10.7	8.1	No	5	0.87	381	2.75	10.9	8.74	6.41	3.3
2133	246	15.0	11.5	Yes	5	0.8	381	13.0	11.88	12.17	9.31	7.8

VII. CONCLUSIONS

The laboratory results indicates that it was possible to sustain arc at 150 Vdc. In some cases the incident was higher than 1.2 cal/cm² but never higher than 1.4 cal/cm². It was possible with an available bolted fault current of 17 kA. The electric arcs were able to be sustain with arc as long as 25 mm (1") before they extinguished. Some electric arcs were able to sustain up to half a second.

The laboratory results indicate that it is possible with a single phase voltage of 240 Vac to sustain an electric arc that produce incident energy greater than 1.2 cal/cm² at a distance of 457 mm (18"). It was possible with an available bolted fault current of 10 kA. In some case even above 8 cal/cm² at 381 mm (15") with a source with an available bolted fault current of 15 kA. The arcs were produced with small initial gap. The electric arcs were able to be sustain with final gap as long as 20 to 58 mm (3/4" to 2¼") before they extinguished. Some electric arc were able to sustain up to 1 seconds.

For 150 Vdc and 240 Vac, it was possible to sustain arc only with the vertical in-line electrode configuration. It was not possible to sustain arc with parallel electrodes even with small gaps. The arcs were blowing out and quickly stopped. Future tests should investigate the effect of a barrier in front of the parallel electrode as found when conductors ends to terminals to evaluate if this configuration could create sustained arc.

Future test should also investigate the minimum required bolted fault current to be able to sustain arc at 150 Vdc or 240 Vac. The required minimum voltage and maximum gap to initiate and sustain an arc above 1.2 cal/cm² should also be investigate. A better exploration and comprehension of these DC or AC single phase limits that could produce arc flash incident energy above 1.2 cal/cm² at a typical working distance will allow a better evaluation which equipment present an arc flash hazard. Even if it is possible to sustain an arc at 240 vac that developed above 1.2 cal/cm² at 457 mm (18"), it might still be difficult to initiate it in real equipment configuration with barrier and larger gaps. It is why more investigation and test are required.

Comparing the laboratory results with the calculated theoretical models values for the 150 Vdc and 240 Vac, it can be determined that the theoretical models typically overestimate the incident energy that would be present when given only the source voltage and fault current.

However, it has also been determined that even if the theoretical values were overestimated from the lab results, the personal protection equipment range of PPE for a maximum of 8 cal/cm² or 40 cal/cm², which were determined from the theoretical formulas and the software models, are still adequate for these two voltages: 150 Vdc and 240 Vac.

Even in the laboratory, an arc could not be sustained with parallel electrodes for 145 Vdc and 245 Vac. The electric arc represents only one danger among others such as: shock, arc blast (flying objects, molten metal), and the abnormal heat produced by overheating conductors. Thermal injuries can still be found at level of hand and arms that are not at the typical working distance. Therefore, it is important to remember that personnel must wear the appropriate PPE needed for the task while performing a live intervention on equipment operated with direct current or AC single phase.

More laboratory tests are needed, and consensus by the recognized experts in the field is required, before the current formulas can be replaced by others that are more representative of the behavior of the electric arc observed during the tests.

VIII. REFERENCES

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IX. VITAE

Kirk Gray currently works as an electrical engineer at Hydro-Québec. He has been involved in the electrical incident energy analysis for this Hydro-Québec. Kirk holds a bachelor’s degree in electrical engineering from Université du Québec (ÉTS) in Québec Canada. Kirk serves on various technical committees and sub-committees including CSA Z462 Workplace Electrical Safety, CAN/ULC-801 Standard on Electrical Utility Workplace and IEEE 1584.1 Guide for the Specification of Scope and Deliverable Requirements. He serves as the Team leader and voting member of Z462 Technical Committee. Kirk is an IEEE and OIQ member.

Simon Robert currently works as an electrical engineer at Hydro-Québec. He has been involved in the electrical incident energy analysis for Hydro-Québec. Simon holds a bachelor’s degree in electrical engineering from Université du Québec (ÉTS) in Québec, Canada. He is also an OIQ member.

Rémi Hallé, P.Eng., graduated from École de Technologie Supérieure (ÉTS), Montreal, in 2006 with a bachelor’s degree in electrical engineering. He completed a specialized university program in electrical power energy in partnership with utilities and industries. Mr. Halle joined BBA, a consulting firm, in 2006. In the past years, he has contributed to the power systems department. He has been involved in numerous short-circuit, load flow, protection, coordination and incident energy studies for industrial facilities, mining sites and electrified railway systems. He has also taught electrical safety and electrical protection systems for industrial clients and at Polytechnique engineering university. Mr. Halle is a member of the CSA Z462 Workplace Electrical Safety technical committee.