Open Series Fault Comparison in AC & DC Micro-grid Architectures

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Abstract—**This paper explores empirical observations of open series fault (arc fault) testing during current interruptions. Emphasis is on dc systems, but arc behavior is also compared to that of ac systems under "quasi-equivalent" circuit parameters. Specific parameters that are considered regarding arc behavior include gap voltage, current, dissipated power, voltage and current transient characteristics, re-ignition, bus disturbances, and contact position during dc arc collapse. Based on these results, comparisons between ac and dc systems seem to indicate that different arc-related challenges exist for both dc and ac architectures.**

Keywords—direct current, open series fault, arc transient, spike, current interruption, micro-grid

I. INTRODUCTION

This paper explores open series fault behavior in ac and dc power distribution architectures. In recent years, the search for higher efficiencies in information and communication technologies (ICT) facilities and the development of alternative approaches for power supply systems, such as micro-grids, have reignited the debate over the choice of ac or dc for power distribution voltage systems. DC systems have been identified to have the potential for higher availability, power density, and efficiency than equivalent, conventional ac systems [6]. Moreover, dc systems seem to be better suited for power supply micro-grids because renewable and alternative power sources, energy storage devices, and many modern loads are inherently dc-based [1]. However, concerns over fault detection and clearance have always limited widespread use of dc systems. Although all dc faults present interruption challenges due to the lack of current zero-crossing, open series faults present particularly complex issues because the current in such faults does not exceed load currents. Thus, these faults are difficult to detect. Open series faults occur at conductor discontinuities, typically caused by aging, vibration, mechanical stresses, excessive temperature, or other causes. At the point of discontinuity, an arc ensues; yet, current and voltage levels remain close to their pre-arc values. Moreover, dc arcs are recognized as a safety hazard which may lead to fires.

Open series faults may also be observed in controlled environments, such as circuit breakers and fuses. Provided a necessary minimum voltage exists in the circuit whenever contacts of a switch carrying current are separated, an arc is established by the high field and local heating at the last point of contact. The duration of this arc depends upon the nature of the contacts that serve as electrodes, the velocity of the moving contacts, the nature of the surrounding medium, and the properties of the electric circuit [2].

The focus of this paper is to experimentally determine the characteristics of open series faults in both ac and dc systems, and to explore the effects that these faults have in terms of local and system disturbances. One of the the targeted voltages studied is 380Vdc because it will likely be the future standard for ICT facilities power distribution systems.

II. OPEN SERIES FAULT CHARACTERISTICS

The conservation of energy principle serves as a valid starting point for the analysis. When applied to an arc, the electrical energy input must be equal to the energy released as heat, pressure, sound, light, and electromagnetic radiation [3]. A fault's current characteristics also depend on circuit parameters. In particular, they depend upon the system inductance. Circuit inductance exists in both dc and ac systems, for example, in power distribution conductors. As it is well known, inductance represents a circuit component in which current's values tend to remain unchanged—i.e., inductance represents a current inertial. As the system inductance increases in magnitude, the rate of change in the fault current is less. If circuit protection elements such as inline fuses are present, this causes the melting time of the fuse also to increase. Hence, the let through energy of the fuse (I^2t) is higher for high system inductance values [4] [5]. Additionally, higher inductances may create instability issues in distributed power architecture with constant-power loads [6].

In principle, the interruption of an ac arc is much simpler than that of a dc arc. At first glance, their advantage with regards to fault mitigation seems clear. The maximum time ac current should sustain itself (excluding re-ignitions) is only half a cycle because the periodic waveform will reach a zero current crossing where the arc should cease. Thus, in principle, the extinction time of an ac arc will not exceed 8.33 ms for a 60 Hz waveform. In the interruption of a dc arc, the circuit breaker must actually force the arc to become unstable. Thus, the interruption of an open series, arc fault in

an ac circuit is simpler than that of a dc circuit of the same power [2]. Therefore, for dc architectures, open series faults initially seem more concerning.

III. EMPIRICAL ANALYSIS

A. Testbed

For the purposes of this experiment, a small micro-grid was built using the following components: 3Φ AC source panel, variac or transformer, 6 diode bridge rectifier (for dc bus architectures), open series fault mechanism, and an RL load. Specific passive parameters for the micro-grid are included in Table I.

TABLE I. PASSIVE MICRO-GRID COMPONENT PARAMETERS

Component	Value	Units
Loadbank (4 series)	$7.68 + 2\pi f(593.0e\text{-}6)$	Ω
Loadbank (2 series)	$3.84 + 2\pi f(296.5e\text{-}6)$	Ω
Loadbank (2 series, 2 parallel)	$1.95 + 2\pi f(145.9e\text{-}6)$	Ω
"Millie" Inductor	$17.0 + 2\pi f(1.3)$	mΩ
"Henry" Inductor	$28.0 + 2\pi f(4.9)$	mΩ
Micro-grid & cabling (without loads)	$11.0 + 2\pi f(63.0e\text{-}3)$	mΩ
Shunt (cable) capacitance	10.0	μΩ
Shunt (cable) resistance	10.0	MΩ

The focus of testing was to create an open series fault during current flow, and monitor specific variables of interest across this fault, namely, the gap current, voltage, and power dissipated. Other particular measurements of interests were bus disturbances, transient effects, arc duration, potential arc re-ignitions, test repeatability, and localized damage to the electrodes. In order to study such effects, an open series fault mechanism was constructed. It consisted of two copper bars *(1" in diameter)*, clamped in place to aluminum blocks. The aluminum blocks served as connection terminals for 262 kcmil cable, used as the bus wire. While one aluminum block was stationary, the other was connected, through isolation, to a mechanically-driven stepper motor. This fault mechanism can be seen in Fig.1:

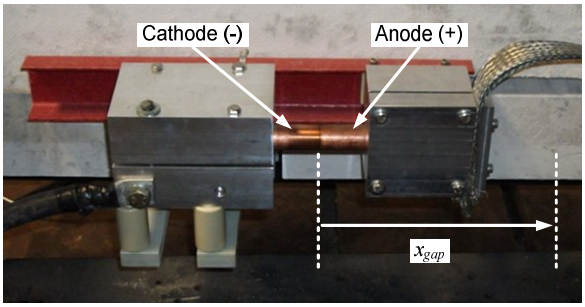

Figure 1. Series Fault Mechanism: Two electrodes separate longitudinally to represent the formation of an open series fault

A control algorithm and GUI were developed to control this motor, thereby allowing the copper contacts to be open and closed at specified rates. The two rates used for this study were a slow opening at constant velocity, (0.1 in/sec), and a faster one opening at constant acceleration equal to the gravity on Earth, or 9.8 m/s^2. The latter was not actually controlled via the stepper motor, but rather a pneumatic valve and compressed air regulator whose pressure was calibrated to achieve the desired acceleration. The slower, constant velocity test was chosen somewhat arbitrarily, while the constant acceleration test was chosen as a worst-case, gravity simulation, such as a cable connection breaking loose and falling.

A Model 40, Integra, Nicolet scope was set to capture one million data points at 12 bit resolution. The trigger mechanism for the oscilloscopes was set to be a change in the copper electrode distance. Additionally, 10% of the data points captured were pre-trigger, to ensure several cycles of acceptable waveforms were captured before the bus fault was initiated.

B. Test Methodology

The first consideration while designing the experimental setup was to avoid equipment damage. Therefore, a variac was initially placed downstream of the 3Φ, 208Vrms AC source panel so voltage could be dialed down to a lower threshold to ensure any fast-acting transients would not exceed rated parameters of the equipment. Once transients were perceived to be safe, bus voltages were steadily increased to higher levels while ensuring current draw would not make ac breakers trip.

For higher voltage testing, a 3Φ, 480Vrms ac source panel was utilized. In order to adjust this voltage to desired levels, an isolated ac-ac transformer was used to step-down voltage until safe operation could be assured. For all ac testing, only 2 phases (line-to-line) were utilized and the 6 diode bridge rectifier used in dc tests was removed from the circuit. For dc testing, all 3 ac phases were rectified to achieve the dc bus voltage level. The rectifier output filter shunt capacitor was removed because its presence would affect the open series fault behavior. Thus, the dc bus waveforms show higher ripple than usual. Like in the ac tests, an upstream variac or transformer was utilized to ensure safe operation before dc bus voltage levels were increased. In order to compare results in ac and electrically equivalent dc systems, main bus passive components parameters (R, L, C) were taken as the baseline reference for the analysis. AC power or rms values of current and/or voltage were not considered as the baseline of comparison because one cannot control where in the ac waveform the open series fault mechanism is triggered to open.

As expected, experimental results indicated that ac arcs extinguished faster than those created under dc conditions. Hence, oscilloscope resolution shows an order of magnitude difference with most ac waveforms being captured at 5μs for the constant velocity test (0.5μs for the constant acceleration test), while most dc waveforms were captured at 50μs for the

same opening conditions (5µs for the constant acceleration test). Still, during the tests, a few, partial dc waveforms were captured at higher resolution to ensure there were no fast-acting transients hidden from view.

C. AC Test Results

AC systems show, visually, little if any arc because the current waveform dissipated very quickly once the circuit pathway was interrupted. Consider the experimental Fig. 2, recorded with Igor Pro©. The open series fault mechanism for this initial, low-voltage, ±44Vac$_{,peak}$ test initiates at 0.46 seconds. At this time, current and voltage waveforms begin to show some disturbances. Yet the current does not cease until it reaches its second zero-crossing. Once the current ceases to flow, a back EMF appears across the gap, resulting in a fast transient ringing or voltage spike *(max 152V, min -64V)*. In the case depicted in Figure 2, this voltage spike across the gap is about 3.5 times the main bus nominal voltage. Since the fault is in series, its voltage would appear to any system element downstream (such as an input capacitor in a power electronic converter) as an addition to the source's ac generated voltage. Hence, in this particular test, any potential system element located downstream would have been subject to voltage levels 3.5 times the nominal values. Since circuit components are typically rated at twice the nominal system voltage, voltage spikes such as the one observed in Fig. 2 have the potential to damage or reduce the reliability of certain components. This is particularly the case in real applications such as electrolytic capacitors or MOSFETs, which are particularly sensitive to surges in voltage.

Keeping the same passive system parameters, the experiment in Fig. 2 was repeated at a higher ac bus voltage of ±70 Vpeak. Results in Fig. 3 show that, this time, the voltage spike *(max 280V, min -270V)* was four times the nominal system bus voltage.

Recognizing these fast-acting voltage transients were of concern, additional system impedance was added in an attempt to magnify this phenomenon. The ac bus voltage was also further increased. Figure 4 shows the experimental results when the system impedance is changed from [7.69 + j(0.247)]Ω, *(1.84º angle)* to [3.896 + j(2.469)]Ω, *(32.37º angle)*, with an ac bus voltage increase to 310 Vpeak. Voltage spikes occur at least in 3 instants with the most significant one reaching about 1 kV, or 3.23 times the nominal system voltage. As evident in Figure 4, this particular ac open series fault actually had three associated arc re-firing instances, each with a transient gap voltage and current spike. The fast-acting transients occurred both during arc propagation and arc cessation. The most likely cause for arc re-fire is the gap voltage reaching breakdown conditions, then being augmented by an air ionization persisting from a previous arc. As the gap between contacts widens, so does the breakdown voltage. Eventually, it reaches a point where gap separation is enough to prevent further arc re-firing events. Voltage spikes during these arc re-firing events are likely caused by the conductor's resistance to fast-changing arc currents due to sufficient system impedance. It is noted that current only ceases to flow at a zero-crossing point. Once voltage spikes as high as 1000 V were observed, tests for higher bus voltages were curtailed due to risks of damaging equipment by exceeding its nominal voltage ratings.

Similar tests to those displayed in Figs. 1 to 3 were also conducted for the faster, constant acceleration open series fault of 9.8m/s^2. Since ac faults collapse quickly, these new series of tests did not provide additional observations than those found in previous tests. However, with these tests it was possible to capture data on the oscilloscope on the fast-acting transients in higher resolution (500 ns) than the slower, constant velocity open series faults of 0.1 in/s (5µs)

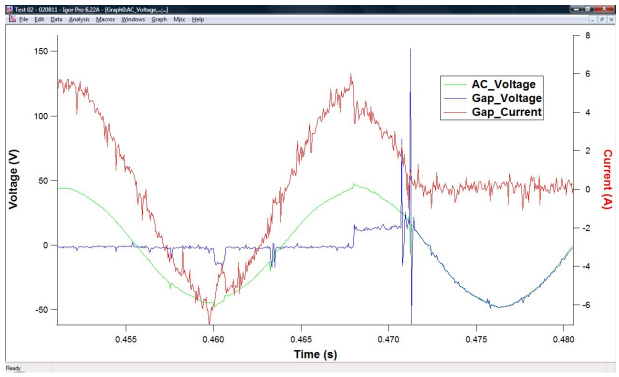

Figure 2. Open Series Arc Fault in 31Vrms ac system

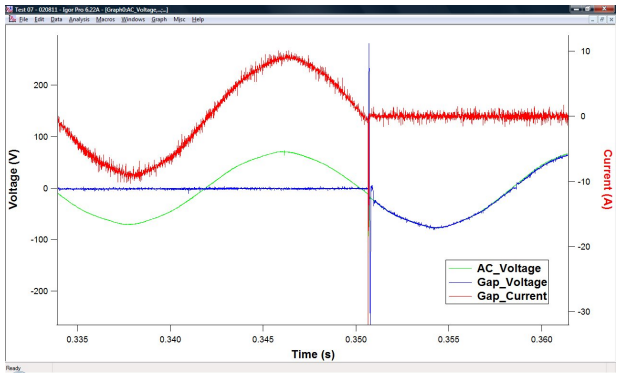

Figure 3. Open Series Arc Fault in 49.5Vrms ac system

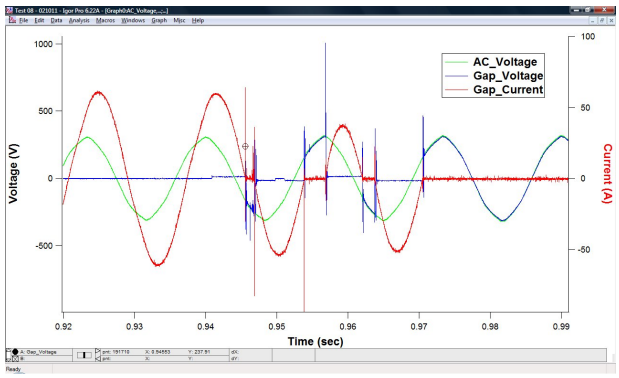

Figure 4. Open Series Arc Fault in 219Vrms ac system with series impedance

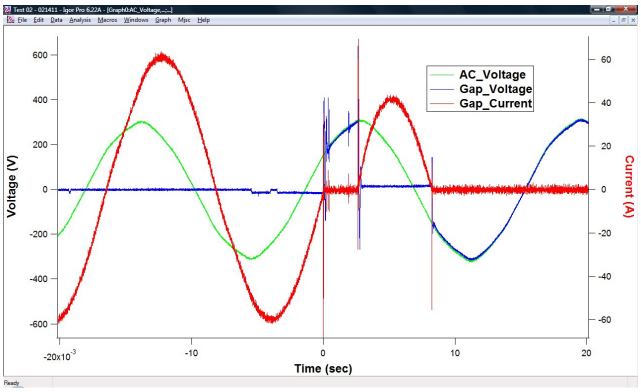

Figure 6. Open Series Arc Fault in 217Vrms ac system with series impedance, under higher resolution

shown in Figs. 2 to 4. Figure 5 shows an experimental plot from one of these higher acceleration tests depicting arc re-ignition and transient waveforms in greater detail. As expected, fewer re-ignitions are observed. In fact, not all ac open series fault testing yielded arc re-ignitions. Additionally, the magnitude of the transient spikes varied between test runs even for the same conditions. The reason for this difference can be found in the inability to control where in the 60Hz ac cycle the voltage and current waveforms were in relation to the trigger signal sent to open the series fault mechanism. Another point worth mentioning is that most accidental open series faults (such as those caused by cable failure) are expected to be similar to those depicted by the slower, constant velocity gap opening tests, for which more arc re-ignition conditions are expected.

A frame from video taken during ac fault testing is also included here, shown in Figure 6. However, arc visual effects were far more noticeable in dc cases.

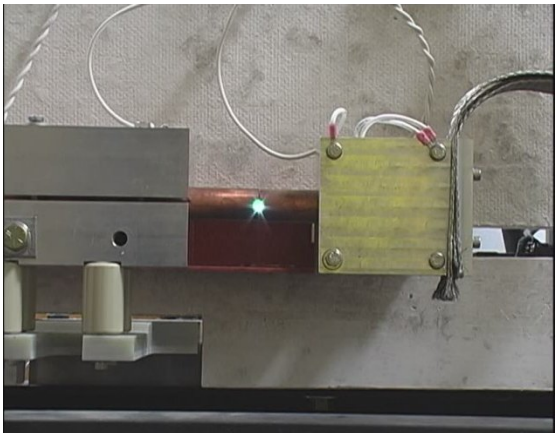

Figure 5. Video Image of an Open Series Arc Fault in 217Vrms ac system

D. DC Test Results

Tests showed that dc open series faults' behavior is very different from that observed in ac systems. As expected, dc arcs persisted for a much longer duration due to the fact there is not a zero-crossing. However, traces of the bus voltage, gap voltage, and current waveforms showed no evidence of spikes. Figure 7 depicts traces from test conditions of a 3 phase, 214Vac(rms) source passively rectified to a 280Vdc bus, with a series RL load of 7.69Ω and 656μH *(same load as in Figures 1 and 2)*, opened under the constant velocity of 0.1 in/s. Here, the dc arc persisted for roughly 5 seconds, up to a maximum of 0.5 inches of gap spacing. Traces show that the current across the gap steadily decreased in almost a linear fashion until such time as the arc could no longer be sustained. Conversely, as current steadily declined, the dc bus voltage increasingly was applied across the arc gap in almost a mirror-image like waveform. Eventually, the arc collapsed and current fell to zero amps with the full dc bus voltage now applied across the entire gap. Yet, no fast-acting transient spikes were observed.

Tests were repeated three times at the same conditions. Test electrodes were polished each time in order to ensure oxidized copper "skin" would not interfere with test results. In all equivalent tests, the relative slopes and time until arc collapse remained constant.

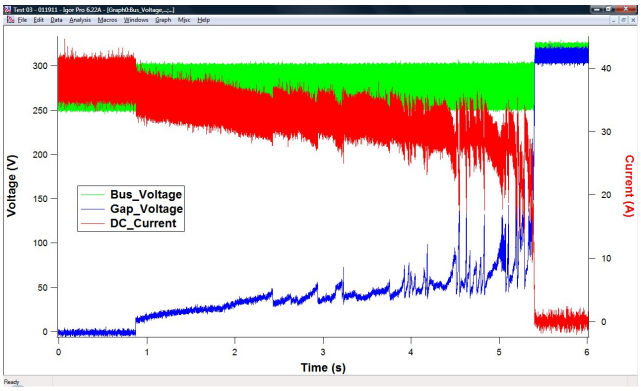

Figure 7. Open Series Arc Fault in 280V dc system

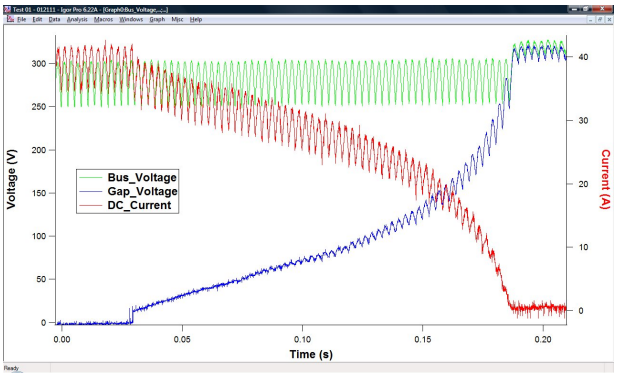

Figure 8. Open Series Arc Fault in 280V dc system, constant acceleration opening, higher resolution

Recognizing that the fast-acting transients observed under ac bus conditions were recorded at higher resolution (5µs and 500ns), the dc bus testing (50µs) was also conducted under the faster, constant acceleration test of 9.8m/s^2 so resolution could be increased by an order of magnitude (5µs) to match that recorded by the constant velocity (0.1 in/s) ac tests. Results with the constant gravity-like acceleration are depicted in Figure 8. These results confirm again that no severe transients occur during dc arc formations or collapse. Additionally, both current and voltage do not evolve linearly as in the constant velocity test. Instead, there is now a power law dependence indicating the transients are highly dependent upon the velocity in which the contacts are opened .

To match the conditions of ac fault testing, a larger series inductance was also introduced into the dc bus to attempt to magnify any possible fast-acting transients. As before, voltage bus levels were steadily increased upon assurance of safe operating conditions. With a series RL load of 3.896Ω, 6.55mH, and an average dc bus voltage level of 195V (52.5 A), a small transient spike was seen in Fig. 9 with regards to the gap voltage upon arc termination. However, the peak value (seen at 50µs of resolution) was found to be only 285V. This magnitude is far less than recorded for ac testing where spike magnitudes could hit four times the bus voltage. Moreover, this represented a "worst case" scenario for this series of dc testing since over 25 test runs were conducted and over 80% did not show a fast transient of any kind.

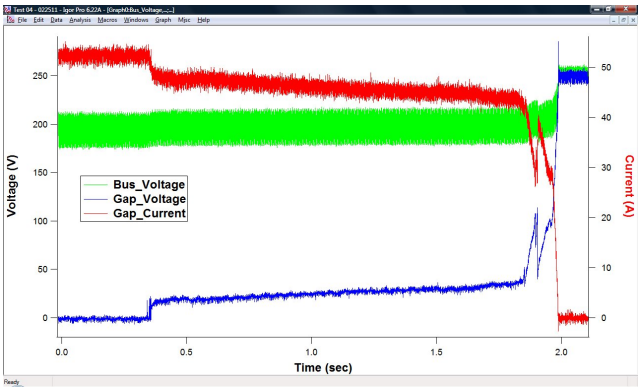

Figure 9. Open Series Arc Fault in 195V dc system, constant velocity opening, with series inductance

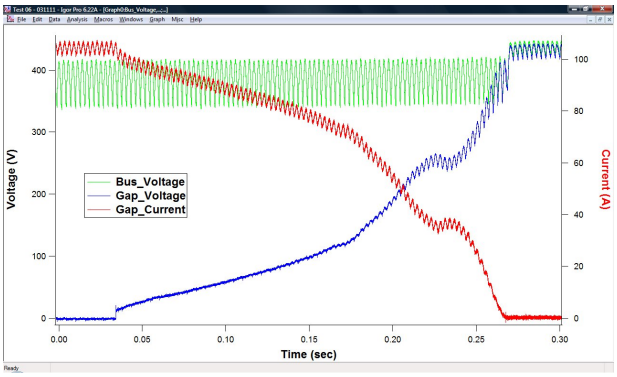

Figure 10. Open Series Arc Fault in 380V dc system, constant acceleration opening, with series inductance

Keeping the same passive components, the dc bus level voltage was increased to 270, 380, and 635V, respectively. Additionally, the faster, constant acceleration tests were also conducted at higher resolution (5µs) to attempt to locate any sharp transients (Fig. 10). None were located in the gap voltage or current, in either the initiation of an open series fault or during sustained arc collapse. At the highest dc bus voltage level recorded (635Vdc), system currents climbed as high as 175A (Fig. 11). At this voltage level, for the constant velocity open series fault of 0.1 in/s, dc arcs persisted across an air gap of 0.7 inches. This length was even greater for the faster, constant acceleration open series faults recorded at 9.8m/s^2. Even at these levels, no fast-acting transients were witnessed.

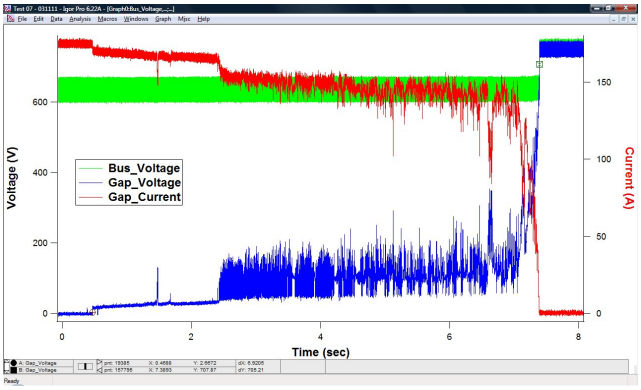

Figure 11. Open Series Arc Fault in 635V dc system, constant velocity opening, with series inductance

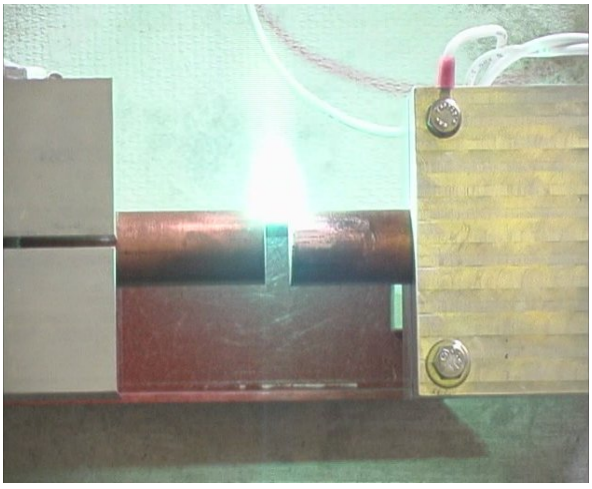

Figure 12. Video Image of an Open Series Arc Fault in 635V dc system

At 635Vdc, 175A of sustained current flow, the copper electrodes began to sustain considerable damage (i.e., vaporized). Therefore, higher dc bus voltage levels and currents were not attempted. As with ac bus testing, video was also captured regarding dc open series faults. A video image of an open series dc fault is depicted in Figure 12.

IV. Conclusions

Notable differences were seen when comparing open series faults in ac and dc architectures. As expected, dc arc faults were more persistent due to the lack of a periodic, zero-crossing point. From a localized standpoint, the higher dc current levels (175A) damaged the copper electrodes and support structures, and may be considered a fire hazard. This localized arc fault damage could not be correlated against equally high current, ac bus voltage tests due to the presence of fast-acting transients in both the gap voltage and current waveforms.

From a system perspective, these spikes in open series ac faults are cause for alarm. With magnitudes of up to four times the ac bus voltage peaks, these transients could damage power electronics switches, capacitors, and other components within the system by exceeding voltage ratings. To counter this problem in ac architectures, one could introduce series inductance or shunt capacitance, but the former solution creates higher voltage drops and negatively affects constant-power load stability, while the latter increases cost. From a dc system perspective, the lack of considerable spikes in the gap voltage or current waveforms is an electrical advantage. Despite the fact open series faults persist for a much longer duration, if power electronics could effectively be utilized for fault isolation, the impact on other distribution laterals would be minimized.

From the results presented herein, the following statement is made (limited to the testing conditions): dc open series faults are electrically benign, but mechanically hazardous; ac open series faults are electrically malign, but mechanically benign.

Future research will explore open series faults downstream of power limiting sources, as well as developing a model for dc arcs. Additionally, detection, fault clearing strategies, and safety considerations regarding dc arcs will remain a strong focus.

Acknowledgment

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(Note: All recorded videos are available for view at: http://www.youtube.com/user/utcem/)

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