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Characterization of Series Arcs in LVdc Microgrids

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***Abstract*—This paper provides an empirical study on series arc behavior in low voltage dc microgrids. The response of an R-L-C dc microgrid abstraction towards series arcs is studied experimentally for varying grid inductance, dc voltages, load capacitances and load currents. In order to account for the stochastic nature of arcs, experiments are repeated multiple times under similar conditions to gain statistical significance. Thereby, insight on percentage occurrence and burn time of initiated series arcs is provided. Load side voltage response is studied to gain insight on the expected peak drop and fall time. This empirical evidence was judged to be a necessary requirement in developing a novel series arc extinguishing method from load side power electronic devices.**

***Index Terms*—arcing, dc arc, dc microgrid, series arc, arc characteristics, protection**

I. Introduction

Sustained series arcs are considered more prominent in dc as compared to ac due to the absence of zero crossing. A novel detection and extinction scheme was proposed in [1] by monitoring the load side voltage drop. This drop occurs due to a sudden electrode specific arc voltage injected in the circuit immediately after initiation as shown in Fig. 1.

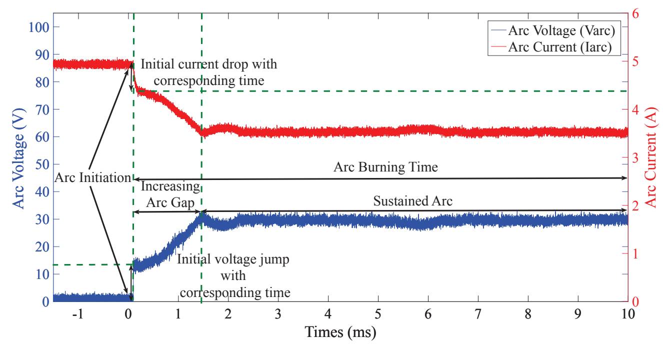

Fig. 1. An example of arc voltage (blue) and arc current (red) waveforms during a series dc arcing event.

It can be observed that at t=0 s, at the instant of arc initiation, the arc voltage immediately appears. Thereafter it rises as the arc gap length increases until about 1.5 ms after which it becomes constant as the arcing electrodes are held constant. Correspondingly, initial fall in the arc current is slower, depending on the circuit time constants. The load side voltage drop in response to the injected arc voltage also varies according to the circuit time constants. The threshold voltage that indicates a series arcing event was experimentally designed for a typical circuit in [2], [3].

It was recognized that the set point of this threshold voltage and the achievable detection time would be sensitive to the grid parameters, particularly grid inductance and load capacitance [4]. At low voltage, low current level, limited characterization studies on dc series arc occurrence and sustainability were found. This paper addresses all these issues experimentally with the larger motivation of supporting a robust detection scheme that the authors comprehensively discuss in [5].

II. Influencing Factors for Characterizing Series Arc Response in DC Circuits

The important aspects in characterizing series arc response in a dc circuit are as follows:

- Chances that the arc initiates.
- Arc burn time and sustainability.
- Load voltage response.

The first two aspects give an understanding of how critical the safety concerns associated with series arcing in a certain system configuration is, while the latter gives the designers insight on defining the set points of the detection algorithm. These aspects depend on several factors governing the state of the larger microgrid. The microgrid is represented as an R-L-C abstraction with a dc voltage source and a capacitor parallelled load as shown in Fig 2.

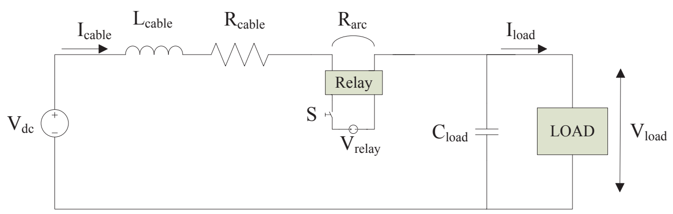

Fig. 2. Equivalent circuit for grid abstraction for series arc characterization.

The following instinctive understanding can be drawn about series arc characterization on various factors:

- Higher the dc supply voltage V_{dc}, arc initiation is more probable and it has a longer burn time. Even though series arcs are a current induced phenomenon, which can be created by drawing apart the electrodes at much lower voltages, there is a certain minimum arc voltage associated. If the series arc is visualized as a dynamic voltage element, this voltage must always be lower than the difference between the supply and load voltage [3]. The question of how strong this dependency is can be answered empirically.
  The load voltage dynamics in response to a series arcing event does not depend on the magnitude of supply voltage [4], but may depend on the dynamics in the supply voltage. For example, in a weak system, a series arc may cause a drop in the supply voltage. In this paper, a stable voltage source with high output capacitance is used.
- Arc current magnitude strongly determines the input arc energy [3], and therefore influences the sustainability of the series arc. The arc channel voltage is also dependent of the arc current, which influences not only the burn time, but also the load voltage dynamics.
- Grid inductance L_{cable} tries to hold the circuit current to its value at arc inception. Therefore, with higher grid inductance, it can be inferred that greater possibility of arc inception exists.
- Load capacitance C_{load} tries to hold the load voltage to its value at arc inception. As discussed earlier, for a series arc to survive, the difference in source and load voltage should be higher than the arc voltage. It can be inferred that with higher load capacitance, it becomes more difficult to initiate series arcs.

An empirical corroboration of the above drawn intuitive inferences will be carried out in the subsequent section. The implications of the influencing factors on the designed series arc detection algorithm will be briefly discussed.

III. Description of Experimental Setup

The actual test environment developed in accordance with the equivalent circuit is shown in Fig. 3. Different circuit elements are highlighted.

The relay is a D-series 12 V Smitt relay that is energized using a switch to induce a series arc in the set-up. This relay is gold plated, for which the average initial electrode dependent arc voltage drop is 14.8 V [6]. This value is greater than that for copper electrodes (13.3 V) for which the operational boundaries are defined in [5]. Therefore, it can be inferred that the occurrence of series arcing will be exacerbated if copper electrodes are employed. Nevertheless, the results presented in this paper based on the various influencing factors will follow the same general trend as discussed in [7].

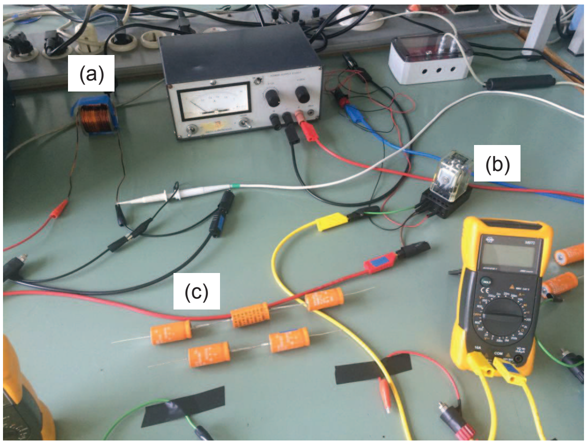

Fig. 3. The practical setup for series dc electric arcing study, (a) Grid Inductance, (b) Arcing Relay, (c) Load Capacitance.

The Table.I summarizes the range in which the test setup parameters are varied during the study.

TABLE I
Parameters for Series Arc Characterization.

Parameters	Symbol	Values
DC source voltage	V_{dc}	$48V$, $75V$, $100V$
Cable inductance	L_{cable}	$100\mu H$, $150\mu H$, $200\mu H$
Load capacitance	C_{load}	$0\mu F$, $17\mu F$, $27\mu F$
Load current	I_{load}	$3A$, $4A$, $5A$
Number of each test	n	6

The source voltage, grid inductance, load capacitance and load current are varied according to values presented in the table. Six experiments are conducted for each circuit condition, giving a total of 486 empirical tests presented in this paper. The voltage before and after the arcing relay is measured with respect to ground to obtain information on arc voltage and load voltage. Load current (which is also the arc current) is also measured.

IV. Result Analysis

This section will explore the empirical evidence of the variation in the percentage arc inception, burn time and load voltage response with different factors such as dc supply voltage, load current, grid inductance and load capacitance. Some results are presented in a visual matrix with these 4 factors as 4-D variation in the outer edges and the dependent parameter depicted as a fifth dimension colour code. In this way, the variation and dependencies become visible and complex interdependencies can be observed in a simple way.

A. Percentage Arc Occurrence

Percentage arc occurrence is defined as the number of times a series arc inception is observed in the circuit. If an arc initiates and eventually extinguishes in time greater than 1 ms, it is still considered a successful series arcing event. Recall that 6 experiments are conducted for each condition to gain statistical significance. Fig. 4. shows the percentage arc occurrence with varying dc supply voltage, inductance, load current and load capacitance.

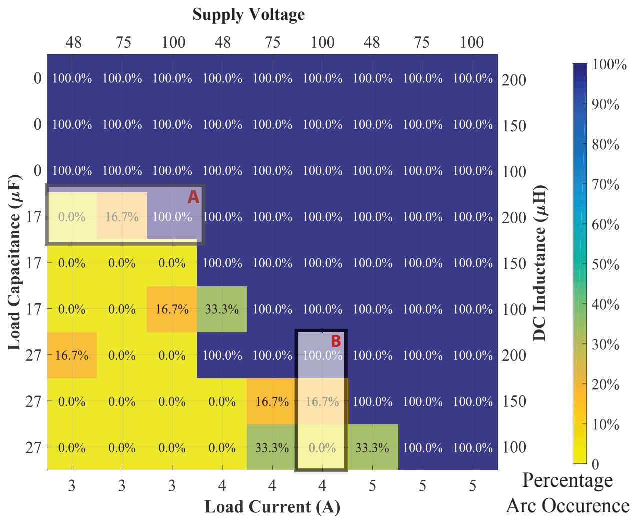

Fig. 4. Percentage times series arc occurs out of 6 tests per circuit condition.

What we can see here is that series arc occurrence is 100 % (6 out 6) in the upper triangle of the matrix. This indicates that the strongest influencers are load capacitance and current. A higher load capacitance holds the voltage much longer than the time required for a series arc to gain enough energy to survive. A lower load current will reduce the input energy to the arc. Clearly, a higher capacitance and lower load current are unfavourable conditions for a series arc to occur. For a 27 μF capacitance and 3 A current at the lower triangle of the matrix, the combined effect of these two conditions ensures that series arc is not initiated.

The region highlighted by block A in Fig. 4 shows that as supply voltage is increased from 48 V to 100 V, the percentage occurrence of series arc increases for the same capacitance (17 μF), current (3 A) and inductance (200 μH). The impact of supply voltage of arc inception is marginal independently, but when seen in presence of a load capacitance, a higher supply voltage will give more time for the arc to stabilize and gain enough energy at its inception.

Region highlighted by block B shows that as the inductance increases from 100 to 200 μH, the percentage occurrence of series arc increases for the same capacitance (27 μF), current (4 A) and supply voltage (100 V). This is because a higher inductance holds the current to its initial value longer and ensures higher energy input to the arc at its inception.

B. Series Arc Sustainability

The sustainability of the series arcs depends on two aspects:

- Arc energy increases with arc current and length. Therefore, an increase in load current would increase the possibility of sustained arcs. Further, as the series inductance in the circuit increases, the arc energy during inception would increase.
- Kirchoff's voltage law is followed according to (1),

$$V_{\text{arc}} = V_{\text{dc}} + V_{\text{L}} - V_{\text{load}} \tag{1}$$

where, the arc voltage V_{arc} is a function of arc current and length given by the emperical relations of [7]. Higher source voltage and lower load capacitance would, therefore, increase the burn time and sustainability of series arcs.

The influence of these two aspects is empirically charted in the matrix colour of Fig. 5 based on varying supply voltage, load current, load capacitance and source inductance.

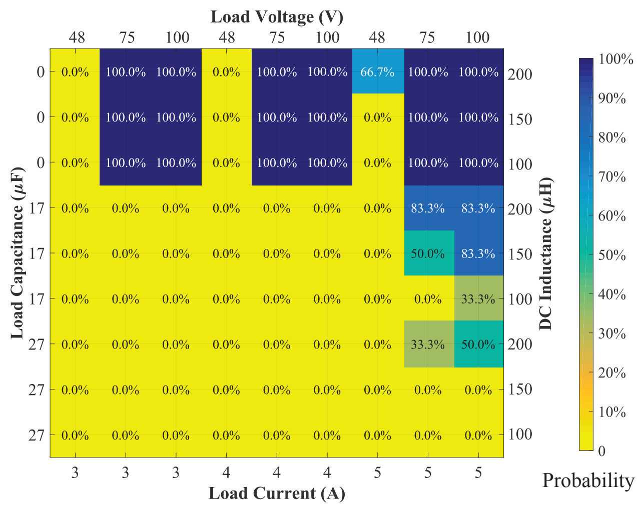

Fig. 5. Percentage times sustained series arcs were obtained.

The results corroborate that a higher source voltage, load current and inductance make it more conducive to obtain sustained series arcs, while higher capacitance makes it more difficult. For example, when the load current is 4 A and capacitance is 0, a supply voltage of 75 V gives sustained arcs 6 out of 6 times, while at 48 V no sustained arc is observed. In this case, build up of arc energy can be assumed to be similar, but the voltage balance reduces the burn time. Same is true when capacitance is increases to 17 μF, at which point, sustained arcs are observed only with higher current and inductance, both ensuring that higher arc energy is accumulated in the channel, thus reducing the arc voltage.

Another interesting observation is the limited dependence on the supplied power level. When supplying a power of 240 W at 48 V and 5 A, no sustained series arcs are observed, while at a lower supply power of 225 W , sustained series arcs are obtained 100 % of the times at 75 V and 3 A. The observed sustained arcs at lower power level shows that difficult voltage balance due to lower supply voltage is more relevant than the instantaneous arc energy corresponding to lower current. It follows that for higher power supplies, high current low voltage operation maybe favourable from series arcing point of view. However, there is a trade-off with the operating efficiency of the system, as the the losses increase at higher operating currents.

A possibility of taking advantage of the voltage balance is increasing the load capacitance from 0 in the previous example to 27 μF. In this scenario, sustained arc is not obtained even in a high power (500 W) operation with a high voltage of 100 V and current of 5 A. Increasing capacitance, therefore not only reduces the voltage ripples and improves the stability, but can also limit the series arcs. Trade-offs are higher cost and space requirements, higher inrush currents and protection issues during short circuit.

In the similar scenario of 27 μF capacitance, 100 V, 5 A supply, sustained arcing possibility increase to 50 % when the inductance is doubled from 100 μH to 200 μH. A lower inductance, is therefore better from this point of view, particularly in high current high voltage operation. Trade-off herein is the current ripple at the output of the source converter.

C. Characterization of load voltage drop to a series arcing event

The empirical measure of percentage arc occurrence and sustainability give some understanding of how to design a system to minimize the extent of damage by unrestricted series arcing events. However, sustained series arcs cannot be completely avoided. In such cases, they must quickly be detected and extinguished through some protection mechanism. The authors had proposed a novel arc extinction method using load voltage drop in [1]. When a series arc occurs, the load side voltage response has a specific signature due to the initial arc voltage, which is unique to the electrode material [6].

In a previous work by the authors [4], it was recognized that this voltage response is sensitive to the circuit parameters. Representing the circuit as a series R-L-C abstraction and the series arc as a constant step drop in supply voltage corresponding to the initial electrode dependent voltage, it was found that the peak drop in the load voltage could be magnified and attenuated based on the quality factor. This has implications while deciding the set threshold voltage of the designed arc detection algorithm. Further, the time taken for the load voltage to drop to its first peak would also vary based on the R, L and C values, thereby influencing the speed of detection. Therefore, a correct characterization of the load voltage response to series arcing event was deemed important in order to define boundaries of detection corresponding to set threshold voltage, detection time and varying circuit parameters.

The first peak of load voltage drop in response to a series arcing event is given in Fig. 6. The value is averaged over 6 experiments for each condition (varying supply voltage, inductance and load capacitance) in order to account for the stochastic nature of the arcing experiments. The corresponding fall time is shown in Fig. 7.

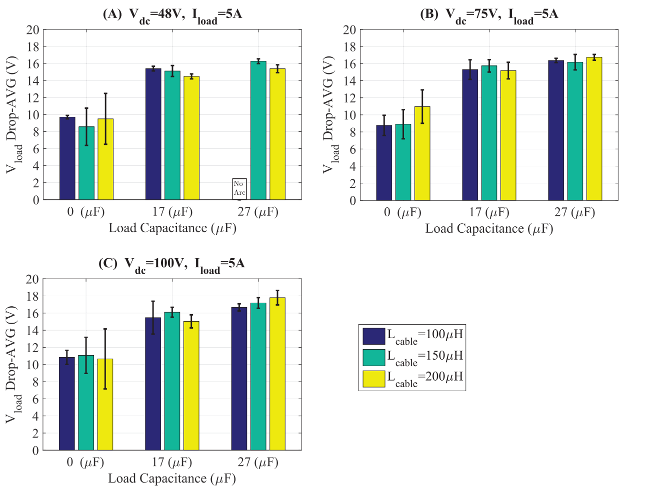

Fig. 6. First peak of load voltage drop in response to a series arcing event averaged over six experiments for each condition.

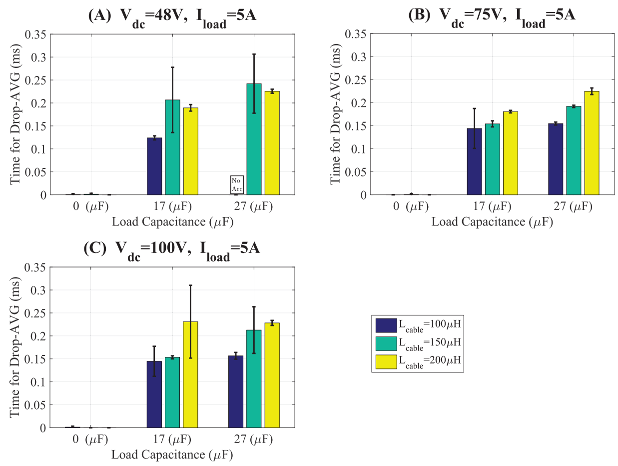

Fig. 7. Fall time to reach the first peak of load voltage drop in response to a series arcing event averaged over six experiments for each condition.

The following dependencies can be observed:

- No clear variation in load voltage response is observed with change in supply voltage.
- When the load capacitance is increased from $0\,\mu$F to $17\,\mu$F, the first peak of the load voltage drop increases because of the amplification due to R-L-C circuit response. The resistance is unknown but it can be inferred that the quality factor of the circuit is greater than 1.
- As the load capacitance is further increased from $17\,\mu$F to $27\,\mu$F, it is observed that the peak load voltage drop increases. This is counter to the decreasing peak to a constant step change in voltage simulated in [4]. This is because the arc is not actually a constant step change, but can be visualized as a gap length dependent increasing dynamic voltage element. As the capacitance increases, the fall time to reach the first peak drop in the load voltage increases. During this time the arc voltage increases and results in a further drop in the load voltage.
- The measured fall time to reach the first peak in load voltage drop increases as the capacitance is increased, as predicted by the simulations in [4].
- As the inductance is increased, a discernable change in load voltage peak is not observed. This is because the change is so small that its within the error margin of the stochastic arcing event. The simulation in [4] predicts a gradual decrease in voltage first peak drop with increasing inductance.
- With increasing inductance, the fall time increases, as predicted by in [4].

The implications of the observed trends in load voltage response on the boundaries of series arc detection algorithm defined in [5] are as follows:

- With increasing capacitance, a constant step arc voltage injection predicts a decreasing peak drop in load side voltage, making it more difficult to detect arcs. In these experiments, we see that the dynamically increasing arc voltage results in actually increasing peak with increasing capacitance. Therefore, it can be inferred that in actual practice, the boundaries defined with a constant step represent the worst case scenario.
- With increasing inductance, the first peak in load voltage drop decreases slightly [4], making it more difficult for the designed algorithm to detect arcs. The detection time would also increase.

Based on the understanding gained from these experiments, some conclusions are drawn and recommendations are made on choosing the safest system design in the context of series arcs.

V. Conclusion and Recommendations

It was observed that percentage series arc occurrence increases with decreasing load capacitance, increasing supply voltage, inductance and load current. The percentage arc sustainability follows the same trend. The increasing inductance and load capacitance would also make the detection algorithm less sensitive and increase the detection time, because the first peak of voltage drop is expected to decrease in worst case, while fall time to reach it would increase. The following practice is recommended in order to minimize the impact of series arcs in dc microgrids:

- Higher load capacitance should be preferred for high current operation as this reduces series arc sustainability. However, it also makes the detection algorithm slower and less sensitive.
- For lower load current, possibility of arcing is already low. If operating efficiency concerns are not too critical and choice of supply voltage is available, the option of lowering the supply voltage could help.
- Source side inductance should be minimized because a higher value not only makes it more possible for series arcs to survive, but also reduces the sensitivity and speed of arc detection algorithm.
- Choose the highest load capacitance and lowest source inductance possible within the detection boundaries defined in [5]. In case sustained series arcs are still possible, the rated operating load current should be reduced.

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