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Real Time Selective Detection of Experimentally Generated DC Series Arcs

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Abstract

Localization of series arc faults in dc microgrids is an important requirement to guarantee operational safety and uninterrupted power to end users. In the previous EPE-ECCE proceeding, a theoretical proof was provided for the selective series arc detection using a novel algorithm. In the current paper, the concept is validated by showcasing real time localized detection when series arc is initiated between point of common coupling and one of the parallel loads. Experiments are repeated several times to gain statistical significance to account for the stochastic nature of the arcing phenomenon.

1 Introduction

Since series dc arc faults are not associated with significant variation in voltages and currents in the distribution system, their detection and localization is difficult. Nevertheless, the damage that can be caused is significant [1]. DC microgrids are more susceptible to series arcs due to the absence of zero crossing in current, and the problem cannot be ignored if safety of the end users is to be guaranteed [2]. At dc grid level, arc fault current interruptors (AFCI) devices are employed at the central bus that can detect an arcing event based on the high frequency noise signature [3], but selective detection is not possible. Further, it is difficult to differentiate between series and parallel arc faults by this method because their noise signature is the same [4]. Low operating voltages of 48 V to minimize series arcs could be a possibility [5], but this solution is not preferred for high power applications due to trade-off in efficiency. With standardization of dc operating voltage around 380 V, efforts have been made to design special plugs to minimize risk to residential users during accidental energized unplugging of equipments [6, 7, 8]. But these are prone to wear and tear, and have added costs.

In the previous EPE proceeding, the authors theoretically showed the selectivity in detecting series arcs [9] using a novel algorithm in a state space simulation model for a series arc between the point of common coupling and one of the parallel connected loads. Developing on the novel arc extinction scheme using load-side voltage [2, 9, 10], the simulated response indicated that it was possible to extinguish the series arc within 10 ms by controlling the load side power electronics to ramp down the load current upon arc detection. The arc detection itself was rapid, within about 1 to 3 ms. This was comprehensively shown experimentally, along with various operational boundaries associated with threshold voltages, grid inductance, resistance and load capacitance in [11].

Considering that series arcing is a stochastic process, and, the load voltage behaviour is highly dependent on grid parameters like inductance and resistance as well as the load capacitance, it was highlighted that the empirical proof of the successful working of the designed algorithm was necessary. It is to be ascertained through repeated experiments that the designed algorithm is statistically reliable and does not fail to trigger during actual arcing event. Thus, the goal of this paper is to experimentally show the selectivity of the designed series arc detection algorithm.

2 Problem Description

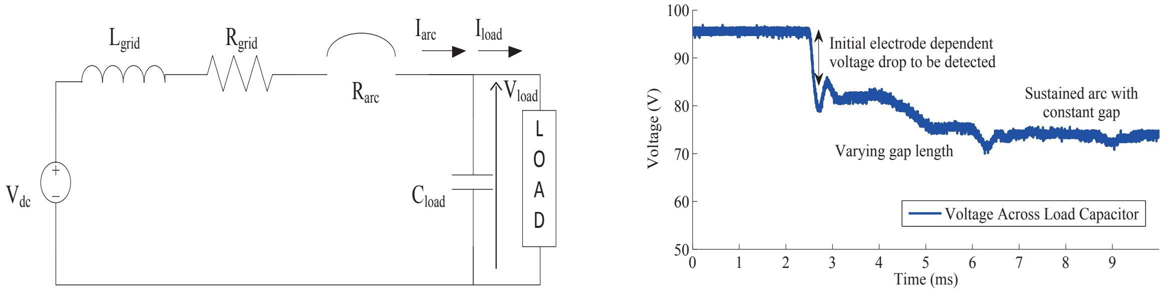
In this section, a background of the designed series arc detection scheme will be offered based on the previous work by the authors [9]-[12]. The problem addressed in the current work will be detailed along with the studied system and test cases.

Background

First, the working principle of the proposed series arc detection algorithm will be briefly described. Subsequently, the structure of designed detection algorithm will be shown.

Working Principle

The series arc detection and extinction scheme based on the load side voltage drop associated with the electrode dependent initial arc voltage is proposed in [10, 11]. An equivalent circuit with dc grid voltage (V_{dc}), inductance (L_{grid}) and resistance (R_{grid}) supplying power to a constant resistance load parallel to a load capacitance (C_{load}) is shown in Fig. 1a.



(a) (b)

Fig. 1: Working principle for series arc detection a) Equivalent circuit with single constant resistance load b) Load voltage measurement during arcing event [11].

The series arc is represented in the figure as a resistance (R_{arc}). An illustration of the load side voltage behaviour when the series arc is experimentally injected in the circuit is shown in Fig. 1b. There is a sudden drop in the load voltage corresponding to the initial electrode dependent arc voltage (the fall time is associated with the resistance, inductance and capacitance in the circuit). Thereafter, the load voltage decreases slowly corresponding to the increasing gap length dependent arc voltage until stabilizing at a point where sustained arc is obtained. The series arc extinction algorithm is designed to detect the initial drop in the voltage which is specific to the electrode material.

Designed Series Arc Detection Algorithm

The designed arc detection algorithm is shown in Fig. 2.

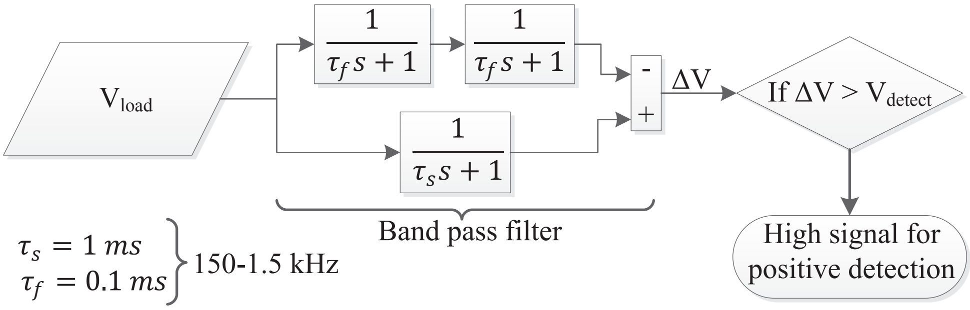


Fig. 2: Designed series arc detection algorithm.

The key component of arc detection algorithm is the bandpass filter which ascertains that there is no spurious triggering due to low frequency grid voltage fluctuations associated with load variations as well as high frequency fluctuations due to switching noise. The time constants and structure of this band pass filter is analytically and experimentally derived in [12]. If the measured load voltage drop from the band pass filter is greater than the set threshold voltage, the algorithm considers this as a series arcing event and outputs a high signal representing a positive detection. Based on this high signal, the controller of the load side power electronic device can drive the load current to zero, thus extinguishing the arc. We restrict our study to obtaining a positive detection signal upon an initiated series arcing event.

Boundaries of Operation

It was observed that there is a finite fall time in load voltage in response to the instantaneous electrode material dependent initial voltage that is injected in the circuit when the series arc initiates. This response is a typical second order behaviour of a series R-L-C circuit depending on the value of grid inductance and resistance, as well as the load capacitance. Some empirical understanding of load voltage behaviour during series arcing events is drawn in [5]. The load voltage response and its interaction with the band pass filter, as the grid inductance, resistance and load capacitance vary, is important in determining the sensitivity of the designed algorithm to trigger at a certain set threshold voltage. In [11], these operational boundaries are comprehensively defined analytically and the sensitivity of the algorithm to varying set threshold voltage is experimentally shown.

System Description and Test Cases

One of the benefits of using this arc detection scheme is the ability to localize the arcing load. This selective operation was theoretically shown in [9] and an empirical proof was deemed important. In this paper, the authors show the selectivity of the algorithm by obtaining real time detection signal when a series arc is introduced in the system. The system based on which the experimental setup was developed is shown in Fig. 3.

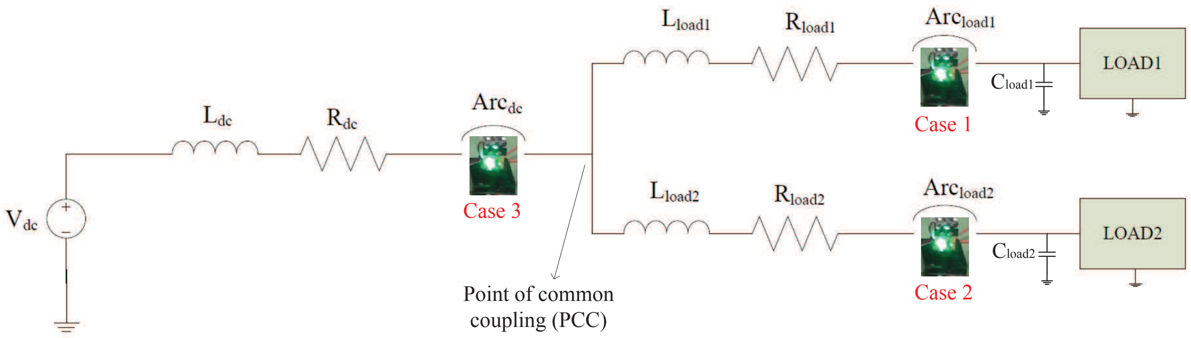


Fig. 3: Equivalent circuit and studied cases.

A stable dc voltage source with inductance (L_{dc}) and resistance (R_{dc}) represent the grid parameters before the point of common coupling (PCC). Using this abstraction, we can recreate the effect of varying grid inductance and resistance on the fall time of the load voltage and the series arc characteristics [5, 11]. Two capacitor paralleled constant resistance loads LOAD1 and LOAD2 are attached to the PCC. Between the capacitors of each load and the PCC, a small inductance and resistance associated with the wiring exists.

In order to study the selectivity, three test cases are explored:

1. In case 1, a series arc Arc_{load1} is introduced between the PCC and LOAD1. It is desired that the positive detection corresponding to only LOAD1 triggers, while the other load continuous normal operation without detecting any arc throughout this experimental condition. The load capacitance and grid inductance is varied and the experiment is repeated 10 times under similar conditions.
2. In case 2, a series arc Arc_{load2} is introduced between the PCC and LOAD2. It is desired that the positive detection corresponding to only LOAD2 triggers, while the other load continuous normal

operation without detecting any arc throughout this experimental condition. The load capacitances and grid inductance is varied and the experiment is repeated 10 times under similar conditions.

3. In case 3, a series arc Arc_{dc} is introduced between the dc source and the PCC. It is desired that detectors corresponding to both the loads send a trigger signal signifying a positive arcing event. The load capacitances and grid inductance is varied and the experiment is repeated 10 times under similar conditions.

3 Experimental Setup

The experimental setup used to prove the selectivity of series arc detection in dc circuits with two parallel loads is shown in Fig. 4.

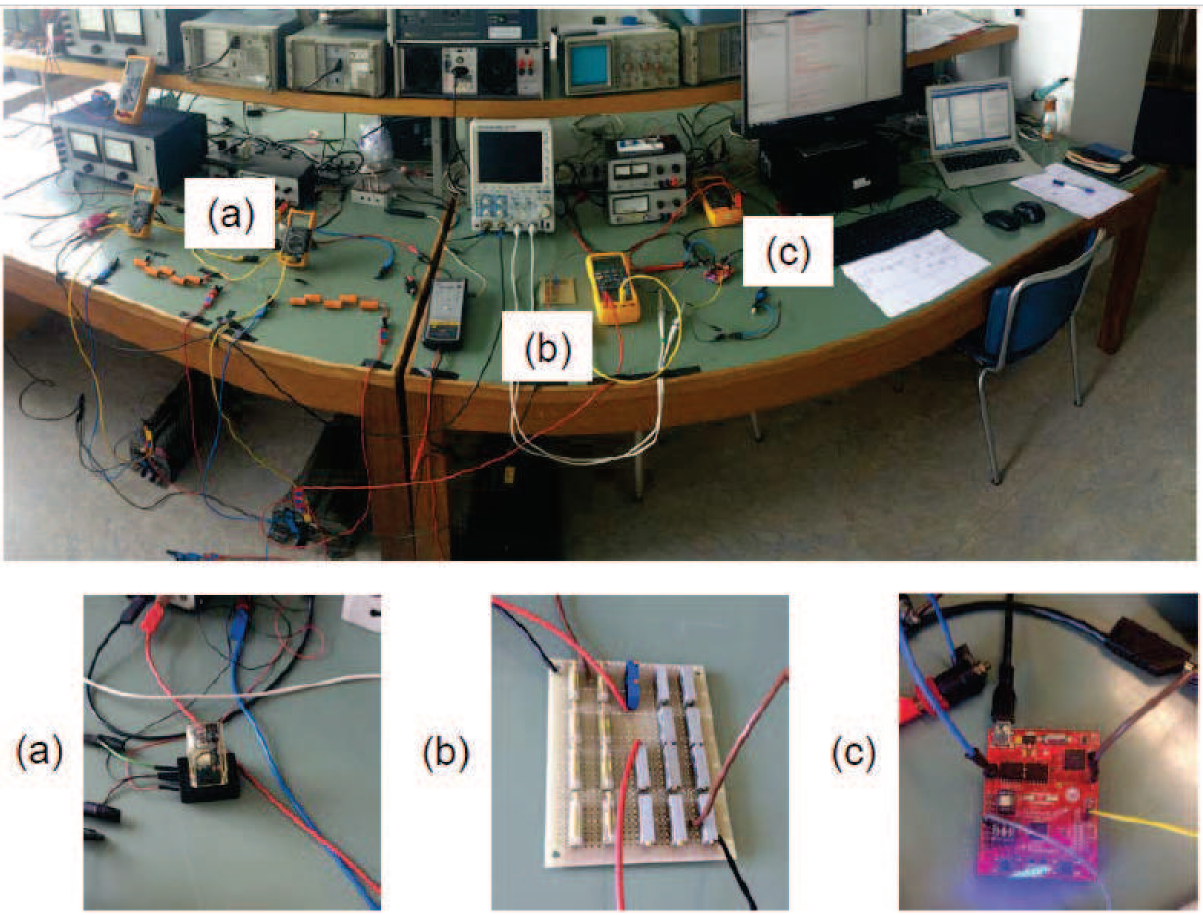


Fig. 4: Experimental set up for selective real time series arc detection.

The 100 V dc supply supplies two 5 A constant resistance loads connected in parallel. The grid inductance used is 200 μH. The load capacitance used are 0 μF and 17 μH for each load. The following components are depicted:

(a) A D-series Smitt relay is operated manually using a dc power supply to introduce series arcs in the circuit at different locations corresponding to the described test cases in the previous section.

(b) The voltage divider measures the load voltages of each load and provides an output of 0-3.3 V adequate for the ADC of the micro controller.

(c) The C2000 micro controller takes ADC input of the measured load voltage of each load and provides an output high detection signal when the set threshold of the internal algorithm is crossed.

The voltage across each load capacitor (C_{load1} and (C_{load2}) is measured and interfaced to the micro-controller via a 1000/3.3 V voltage divider. The designed series arc detection algorithm described in Fig. 2 is programmed corresponding to each load voltage with a set threshold voltage of 6 V. A high positive detection signal (0 to 3.3 V) from the micro-controller is used to trigger the oscilloscope. The interface of the measurement circuit of Load 1, the microcontroller and oscilloscope is shown in Fig. 5.

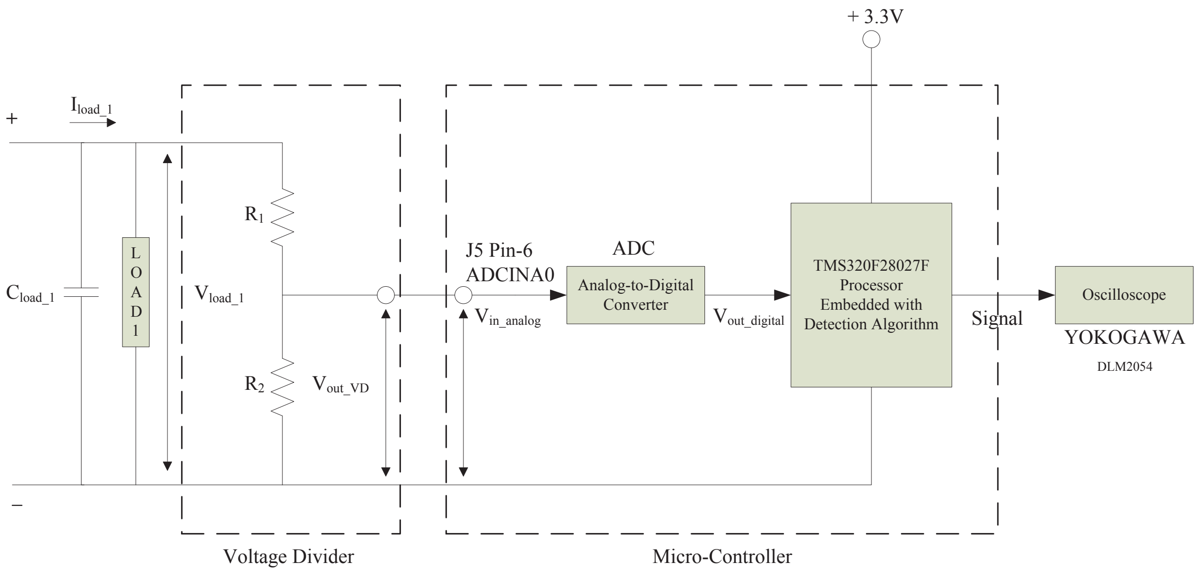
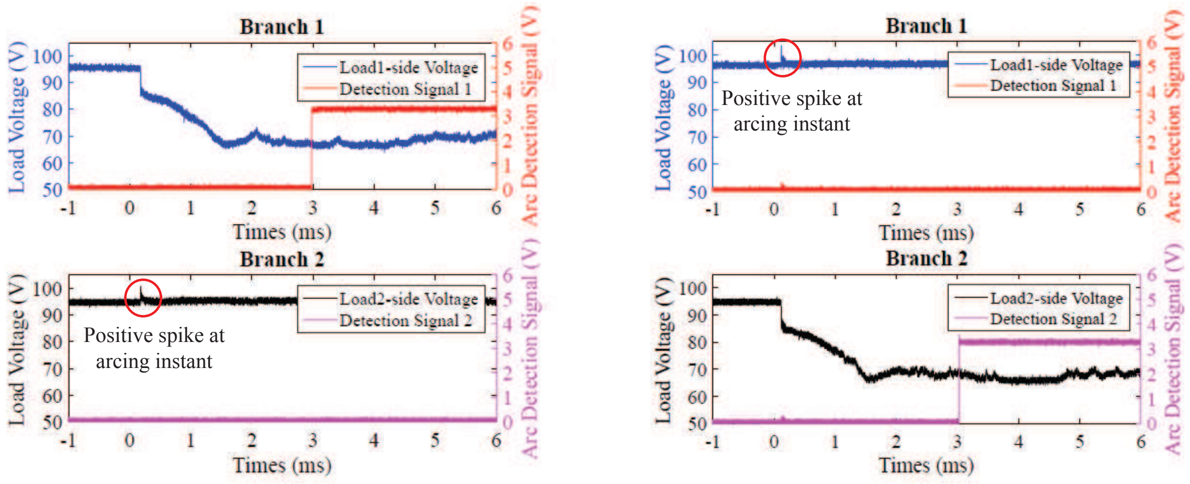


Fig. 5: Interface between the measured Load 1 capacitor voltage, voltage divider, micro-controller and the Oscilloscope.

4 Result Analysis

The real time arc detection for Case 1 and Case 2 are shown in plot (a) and plot (b) of Fig. 6 respectively.



(a) Arcing at branch 1

(b) Arcing at branch 2

Fig. 6: Real time arc detection for a 100 V supply with 5 A load current.

As observed, when $\text{Arc}_{\text{load1}}$ is introduced in the circuit, the detection signal corresponding to arcing load 1 (red colour) goes high within 3 ms while the detection signal corresponding to healthy load 2 (pink) remains low as shown in plot (a). In the second case, when $\text{Arc}_{\text{load2}}$ is introduced, the detection signal corresponding to arcing load 2 (pink colour) goes high within 3 ms while the detection signal corresponding to healthy load 1 (pink) remains low as shown in plot (b). From this sample experiment, we can empirically conclude that selective detection of series arcs is possible.

During the series arcing event, a small positive spike is observed in the load voltage of the non arcing load, as highlighted in the figure. This is corresponding to the positive excursion of PCC voltage due to the inductance between the PCC and the loads in response to the arc injection. The spike will be greater as the inductance increases and lower with higher load capacitance. The magnitude of the peak of the spike is negligible (within few volts and quickly damps out), nevertheless, since the arc detection algorithm is designed to detect drop in load voltages, it is insensitive to the positive transient spike.

Fig. 7 shows the real time results when $\mathrm{Arc}_{\mathrm{dc}}$ is introduced in the circuit. As desired, both loads connected in parallel at the PCC positively trigger.

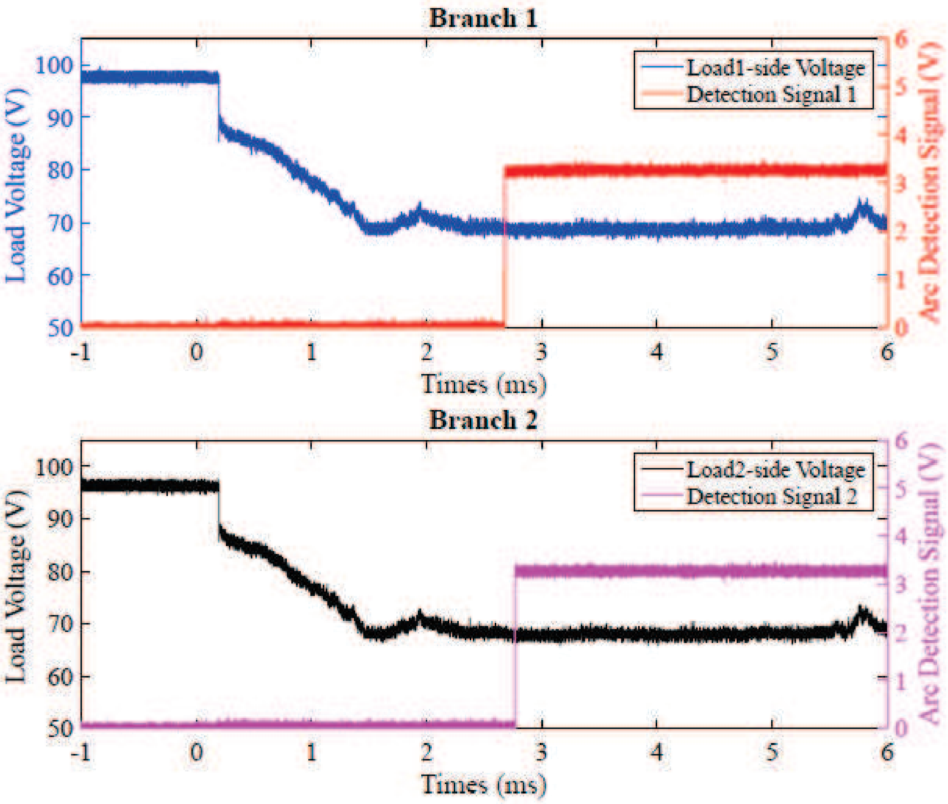


Fig. 7: Real time arc detection for a 100 V supply with 5 A load current for arcing between dc source and point of common coupling (PCC).

In order to get confidence over the statistical reliability of the selective arc detection algorithm, the experiments were conducted 10 times repeatedly for each case for a load capacitance of $0\,\mu$F and $17\,\mu$F. In all 60 tests, the expected trigger profile corresponding to the sample measurements shown in Fig. 4 and Fig. 5 were obtained. Therefore, algorithm works robustly towards the stochastic response of the circuit to series arcing. Further, a higher capacitance did not effect the statistical reliability to selective detection.

5 Conclusion and Future Work

It was shown through experiments that the series arc detection scheme works selectively in identifying which load is arcing. The real time detection provides a positive signal to the introduced arcing event in about 1-3 ms. The health load which is not in series with the introduced arc remains undisturbed.

The tests, repeatedly conducted by introducing series arcs at different locations of the system, show selective positive detection each time. No miss triggering is observed for two different load capacitances, indicating robustness towards stochastic response of the circuit towards series arcs.

Future research work on this topic includes the following:

- Exploring empirically the sensitivity of the detection algorithm to varying grid inductance and load capacitance.
- Proving the robustness of the detection scheme to low frequency grid voltage fluctuations (below 100 Hz) corresponding to load variations.
- Showing the robustness of the detection scheme to high frequency grid voltage fluctuations (above 1.5 kHz) corresponding to switching noise.
- Determining analytically the maximum magnitude of the grid voltage fluctuation with frequency lying outside the 100 Hz-1.5 kHz band to which the algorithm remains insensitive. This may depend on the circuit parameters such as grid inductance and load capacitance. Therefore, the boundaries should be comprehensively defined taking this into account.
- Showing, through typical experiments, the coordinated detection of series arcs in a dc microgrid including multiple switching devices attached as sources and loads to the PCC.
- Implementing the series arc extinction scheme in the load-side power electronics practically, using the designed detection algorithm.

The focus of this research in the current and previous papers has been on the detection of series arcing. Different aspects were explored such as designing the algorithm sensitive to specific frequency spectrum, defining operational boundaries associated with different system conditions, showing sensitivity to set threshold voltages and finally, proving the selectivity and robustness of the scheme. The proposed use of this detection scheme is to ramp down the load current using the load side power electronic device, thus achieving localized extinction of series arcs.

Auto re-connection of the load after a pre-defined dead time following the triggering of the designed algorithm can be an added layer of protective control. This will ascertain that in case of rare misfiring, or clearing of series arc, automatic load energization is guaranteed. The dead time should be decided carefully, making sure that the series arc does not re-ignite. Standardized operating practices should be recommended in future as operational experience with this scheme grows.

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