Inverter Design with High Short-Circuit Fault Current Contribution to Enable Legacy Overcurrent Protection for Islanded Microgrids

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Abstract— **The resiliency offered by a microgrid may be lost if the microgrid is not properly protected during short-circuit faults inside its boundaries. Many studies conclude that protecting microgrids in islanded mode is very challenging due to the limited short-circuit capability of distributed energy resources (DERs). The limited short-circuit capability of DERs typically inhibits the use of reliable and affordable overcurrent protective devices in microgrids. Although extensive research on microgrid protection is available in the literature, to date this research has not led to a cost-effective, commercially available relay that effectively tackles the challenges of microgrid protection. This work proposes hardware modifications to enhance the current contribution of an energy storage inverter with the objective of enabling the use of legacy overcurrent protection for islanded microgrids. This paper demonstrates through experimental results that few modifications are required in the inverter to significantly enhance its current contribution. In this study, a three-phase energy storage inverter was modified to provide three times its rated current during three-phase faults, which proved sufficient current for enough time to enable fuse-relay, and relay-to-relay coordination. The proposed modifications effectively increase the current contribution of the inverter, which is a promising advancement to allow the adoption of overcurrent protective devices for protecting microgrids.**

Index Terms—**Microgrid Protection, islanded microgrid protection, energy storage, adaptive relay, overcurrent protection**

I. Introduction

Microgrids have been identified as a critical component for improving power reliability, increasing energy system efficiency, enabling higher integration of renewable energy sources, and providing energy independence from the grid to end-users. Microgrids have been defined in multiple ways in the literature [1-3]. In essence, a microgrid is a section of the electric grid that retains its connection to the centralized grid most of the time but can "island" itself and operate for hours or even days at a time independently from the centralized grid.

The ability of microgrids to work independently from the main grid makes them a resilient system because they can power local loads when the main grid is unavailable. However, this resilience is lost if the microgrid is not properly protected during short-circuit faults that occur within its own boundaries [4]. To maintain reliable operation, the protection scheme in a microgrid must be capable of meeting the protection requirements of selectivity, sensitivity, and reliability for both grid connected and islanded modes of operation.

Although microgrids are commissioned at the distribution level, the available protective devices for distribution, such as reclosers, relays and fuses, are not suitable for microgrid protection due to the dependence of these devices on the magnitude of the fault current [5]. In microgrids, the short-circuit current magnitude drastically changes between grid-tied and islanded operation [4], [6]. During grid tied operation, the short circuit current ratio is between 10-50 p.u. During islanded operation, the short-circuit current capacity is significantly limited due to the relatively small Distributed Energy Resource (DER) installed in the microgrid, which reduces the available short-circuit current between 1.2-2 p.u. [7-10]. Such a large difference makes coordination of existing distribution protection based principally on existing overcurrent devices difficult and often unattainable [4]. Fuses are particularly affected because of their inverse characteristics; in some cases, fuses protecting the laterals will not melt for faults during islanded operation [4,11].

The issues of low short circuit current and high variability between operating modes have created the need for microgrids to start using protective devices that are not dependent solely on the current magnitude. Currently, line current differential protection is the best commercially available solution to overcome the challenges of protecting microgrids during islanded operation. This method is practically unaffected by both the small fault current from distributed energy resources (DERs) and the variable fault current from grid tied to islanded operation. However, line differential protection is a very pricey solution because a relay should be installed at every node of a protection zone, which may be unfeasible due to the high number of nodes in a microgrid [4].

Adaptive protection is a promising technique that enables the use of overcurrent relays in microgrids. Adaptive protection can be defined as an online process which modifies the preferred protective responses and correlates them to a change in system conditions or requirements in a timely manner

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through control or signaling [15]. Adaptive protection can be implemented using a central or decentralized or hybrid approaches [16]–[17]. Adaptive protection methods are expected to be used in microgrids in the future but requires the construction of an extensive and robust communication network. Furthermore, the relay manufacturers should consider enabling modifying the settings of the protection curves online to fully exploit the advantages of adaptive protection. Another obvious disadvantage is that this method does not tackle the root problem of low current, impeding the use of affordable fuses to protect the microgrid laterals during islanded operation.

Most of the protection methods proposed in the literature passively tackle the negative effects caused by the low-fault contribution of DERs. However, to the best knowledge of the authors, there has been no studies that propose solutions at hardware or control level to enhance the short-circuit capabilities of DERs. In this paper, hardware modifications are proposed to increase the fault current of the inverter-based distributed energy resources. The proposed modifications allow an inverter that is designed for 1.0 p.u nominal current to provide 3.0 p.u of fault current for enough time to enable the utilization of legacy overcurrent protection devices. Although the proposed solution is promising in enabling overcurrent protection in microgrids with central energy storage, additional research must be done in the context of a complex microgrid consisting of multiple nodes and distributed generation.

The proposed modifications can be implemented for both PV and energy storage (battery) inverters, which makes it different from solutions previously proposed in [12]-[14], which require a dedicated or overrated unit (e.g., flywheel [12], [13], supercapacitor [14], etc.) to provide high current during faults. It will be demonstrated through experimental results that by increasing the current rating of the semiconductor devices, while keeping all other components at rated power, is sufficient to increase the short-circuit contribution of the inverter. Because of the short duration of a fault, the power losses on the passive components, such as the grid filter inductor and inverter DC-link capacitor, is insufficient to cause permanent damage. This paper studies in detail the thermal response of the semiconductor during a fault at the ac side. Other concerns such as reliability and the power losses of the other passive components will be addressed in future work. Some of the advantages of the increasing the fault contribution of DERs using the proposed method are: 1) Enables the utilization of affordable overcurrent devices such as fuses, breakers and reclosers; 2) Enables fuse-relay coordination, and coordination between primary and backup relays; 3) It is cost-effective since only the semiconductor is oversized, while the rest of the inverter components remain at the designed rated power; 4) No dedicated or additional unit is required; the ES or PV inverter can be modified to provide the higher fault current.

This paper is organized as follows: Section II presents the proposed methodology to increase the short-circuit currents of three-phase inverters. Section III presents the electro-thermal modelling for the inverter under study. Section IV shows the experimental results and compares the thermal response of a three-phase battery storage inverter with a rated and overrated IGBT module under three-phase faults. Finally, section V shows that the proposed design enables fuse-relay, and relay-to-relay coordination in islanded microgrids.

II. System Description and Methodology

A. Microgrid Test Description

The microgrid topology for this study consists of a two-level battery storage inverter, a primary and backup SEL 651 reclosers, and fuse at the end of the circuit rated at 1.25 p.u the lateral rated current (which is typical oversizing for fuses) where 1.0 p.u is 10 Arms. The inverter under test is a classic two-level three phase energy storage inverter, which is composed of energy storage device, three IGBT bridges, an inductive grid filter, potential transducers (PTs), and current transducer (CT), and a control system is implemented on a National Instruments CRIO-9039. The DC-link is coupled directly to the DC-supply without additional dc-dc converter. An input analog card (NI-9220) is used for measuring three phase current and voltages (v_{abc}, i_{fabc}). A digital output card NI-9401 provides the firing signals for the IGBT module. For this study, the battery storage is considered as a constant DC-supply and only the inverter control is considered. The inverter is controlled as the grid forming device. The time current curves (TCC) for the primary relay, backup relay, and fuses are presented in Figure 2.

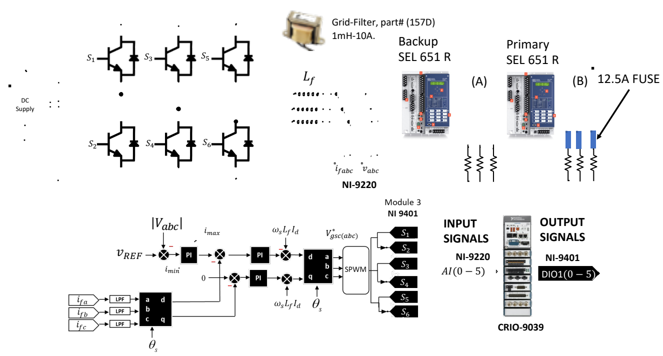

Fig. 1. Experimental setup for evaluating ac faults in three-phase inverters. Rated device (STGIPS10K60T, 600V/ 10A). Overrated device (STGIPS30C60T-H, 600A, 30A). 1mH-10A Inductive grid filter.

B. Methodology

The objective of this work is to demonstrate that an inverter can be modified to increase the short-circuit capabilities by only overrating its power module. Because the overcurrent protection acts in the order of cycles, the inverter only must withstand the high-fault current for a short period of time, which limits the stress in the grid-filter and DC-link capacitor. Of the inverter components, only semiconductor devices should be overrated to account for higher currents. The power module should be oversized to remain in its safe operation temperature during the faulted condition; for silicon that temperature is typically 150 ℃. From an economic point of view, this approach is cost-effective, since for the same manufacturer of IGBT module, for every doubling of cost the nominal current triples [20]. Because the power module accounts for 12% of the

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inverter cost, the proposed inverter with overrated semiconductor modification would increase the cost of the inverter by 8.7%, based on [19]. Other modifications include the current transducer, because it must be able to measure higher currents that are needed for the current controller. It is important to point out that the grid filter saturates when operating at current higher that its nominal. From a protection standpoint, this non-linearity has a small effect on the value of the rms current. However, from a control standpoint, the core saturation reduces the available inductance, which impacts the stability of the current control loops. In this work, the current controllers were designed to maintain the phase and gain margin for current exceeding three-times the nominal inverter current.

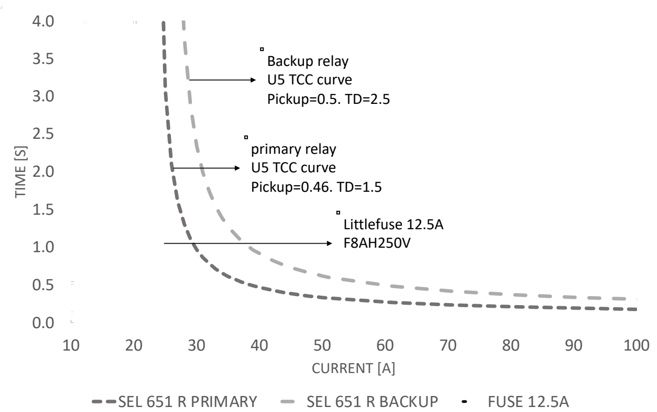


Fig. 2: TCC curves for the 12.5A fuse. SEL 651R used as primary and backup relay. The CTs for both relays are 50-1 ratio. The pickup for the primary relay is 0.46 with a time dial of 1.5. The backup relay has a pickup of 0.5 with a time dial of 2.5. U5 curve for 51 protections is used for primary and backup relay.

III. POWER LOSSES IN THREE-LEVEL INVERTER

This section develops an electro-thermal model to estimate the temperature response of the semiconductors during faults in the ac side. The power losses can be divided into conduction and switching losses of the IGBTs and their associated anti-parallel diodes. Switching losses happen during the turn ON and turn OFF transients and are proportional to the switching frequency $1/T_o$, the collector current i, and blocking voltage V_{dc}. The conducting loss can be calculated with the saturation voltage drop V_{CE} and the collector current i, multiplied by the instantaneous duty ratio τ. For this study τ correspond to sinusoidal PWM (SPWM). The set of equations to calculate the inverter losses are presented in Table I.

Table I. IGBT Switching and Condition Losses [18]

	SWITCHING	**CONDUCTION**
IGBT	$\frac{1}{T_o}\sum(E_{on}+E_{off})\frac{i}{I_{nom}}\frac{V_{dc}}{V_{nom}}$	$V_{CE}(T_{IGBT}, i)\, i\tau(t)$
DIODE	$\frac{1}{T_o}\sum(E_{rec})\frac{i}{I_{nom}}\frac{V_{dc}}{V_{nom}}$	$(V_{T0}(T_{diode})+r_T(T_{diode})i)i\tau'(t)$
$\boldsymbol{\tau(t)}$	$\frac{1}{2}(1+m\sin(\omega t+\emptyset))$	$\frac{1}{2}(1-m\sin(\omega t+\emptyset))$

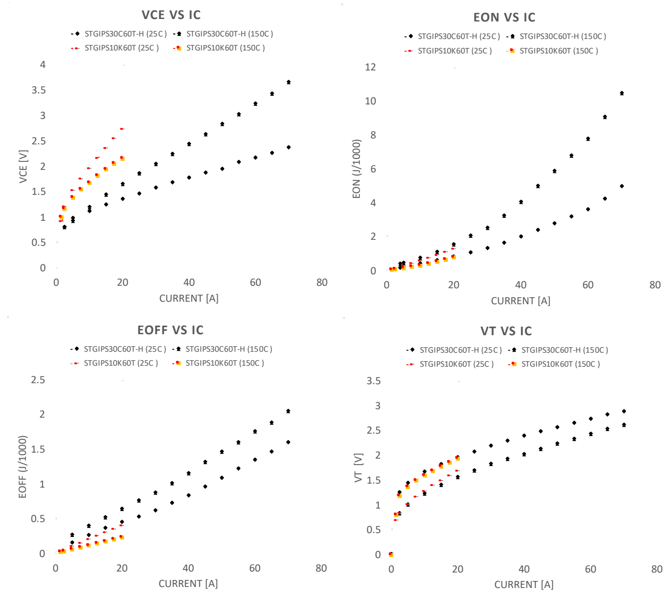
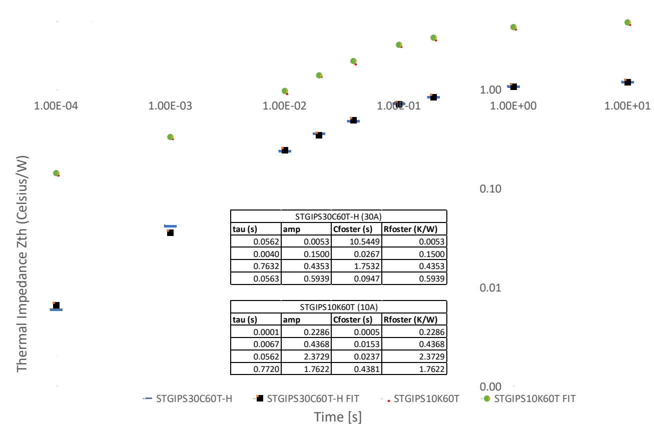


Fig. 3: ST intelligent modules used in the study. Rated device (STGIPS10K60T, 600V/ 10A). Overrated device (STGIPS30C60T-H, 600A, 30A).

Fig. 3 presents the information regarding the rated and overrated semiconductor devices used in this study. As shown, the following parameters are sensitive to the collector current: V_{CE}, V_T , E_{on}, E_{off}. During a fault, the increased collector current influences these parameters rapidly incrementing the conduction and the switching losses, which further increases the junction temperature. Fig. 3 presents the thermal impedance of the devices which is used for the electro-thermal modelling. The curve fitting was done by minimizing the root mean square error. The accumulative percentage error is 2.2% for the 30 A device and 1.1% for the 10 A device, which is considered a very good fit. The IGBT junction and diode temperature are calculated using a four-layer, RC Foster network, the thermal capacitances and resistances are also included in Fig. 4.



STGIPS30C60T-H (30A)			
tau (s)	amp	Cfoster (s)	Rfoster (K/W)
0.0562	0.0053	10.5449	0.0053
0.0040	0.1500	0.0267	0.1500
0.7632	0.4353	1.7532	0.4353
0.0563	0.5939	0.0947	0.5939

STGIPS10K60T (10A)			
tau (s)	amp	Cfoster (s)	Rfoster (K/W)
0.0001	0.2286	0.0005	0.2286
0.0067	0.4368	0.0153	0.4368
0.0562	2.3729	0.0237	2.3729
0.7720	1.7622	0.4381	1.7622

Fig. 4: Thermal impedance and fit using Foster RC network for the 10 A/600V module and 30 A/600V module.

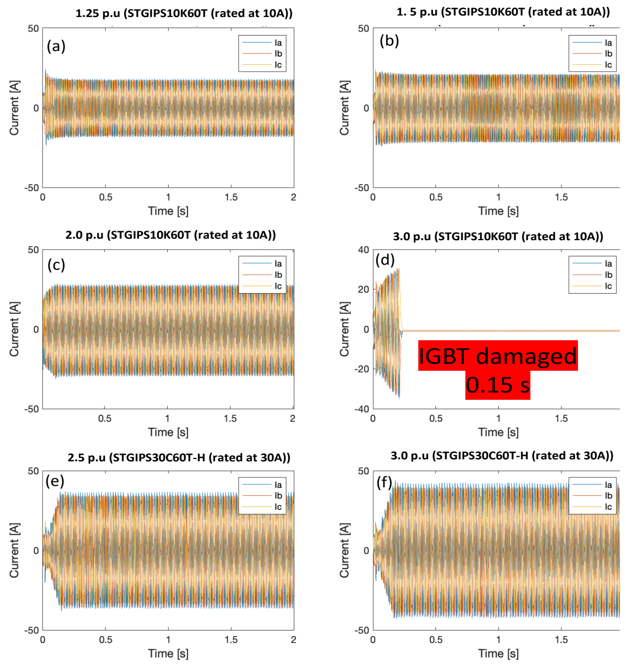


Fig. 5. Experimental results showing inverter current during three-phase faults. Rated device providing the following fault current: (a) 1.25 p.u, (b) 1.5 p.u, (c), (d) 2.0 p.u (d) 3.0 p.u. Overrated device providing the following fault current: (e) 2.5 p.u. (f) 3.0 p.u.

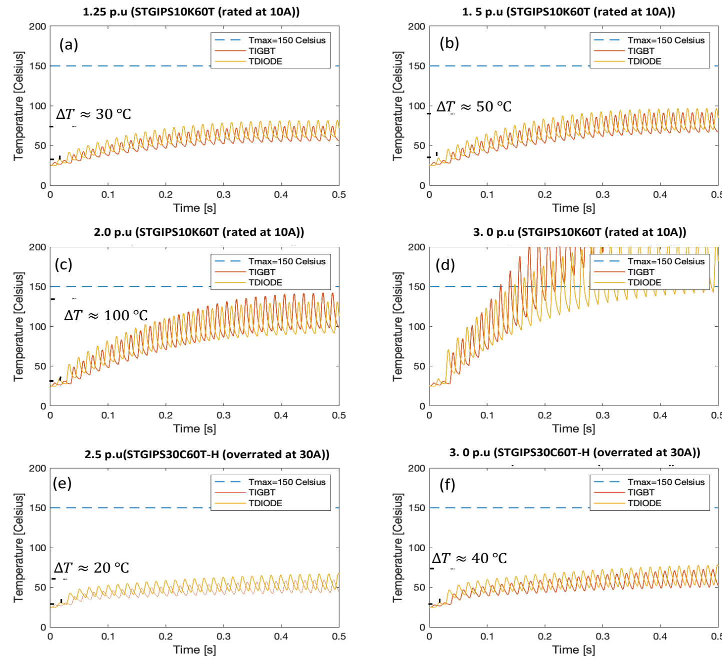


Fig. 6. Simulated temperature response using 4-layer Foster network for the following cases: Rated device providing the following fault current: (a) 1.25 p.u, (b) 1.5 p.u, (c), (d) 2.0 p.u (d) 3.0 p.u. Overrated device providing the following fault current: (e) 2.5 p.u. (f) 3.0 p.u.

IV. Experimental Results

This section first studies the limitation of inverters with rated semiconductors to provide short-circuit current. Following, the same inverter is modified with the overrated semiconductor to show that it can safely provide high short-circuit current. Because the interest of this test is revealing the short-circuit capabilities of the inverter, the unit under test is isolated from the protective devices of the microgrid. Then, the protection devices are introduced in the microgrid to study the feasibility of the proposed modification to enable the utilization of legacy overcurrent devices for protection.

A. Rated Device Three-phase Faults

The first tests consist of evaluating the short-circuit capabilities the semiconductor rated at the inverter rated power (10A). For this, a low-impedance three-phase fault at the end of the circuit is applied, see Fig. 1(c). The inverter with the rated device is controlled to provide 1.25 p.u (typical for PV inverters), 1.5 p.u, 2.0 p.u and 3.0 p.u [12.5 Arms, 15 Arms, 20 Arms and 30 Arms]. The maximum short-circuit current allowed is controlled by the saturation block of the voltage controller, $[i_{max}, i_{min}]$ in Fig.1.

As seen in Fig. 5 (a) and Fig. 6(a), the rated device can easily withstand faults with 1.25 p.u. For this fault, the increase in temperature in the IGBT junction compared to pre-fault state is small ($\Delta T = 30$ °C). In other words, this device can provide this fault current even if the device operates at high temperatures. Fig. 5(c) and Fig. 6(c) show that rated device can provide 2.0 p.u. its rated current. However, at this current the temperature swing is 100°C. In other words, if the initial temperature of the device exceeds 50°C the junction temperature will go beyond the device maximum operating temperature (150°C), which would permanently damage the power module. Finally, the inverter was programmed to provide 3.0 p.u of fault-current. Fig. 5(d) shows that at this current the device has a catastrophic failure after 0.25 seconds. Fig. 6(d) shows that the device rapidly surpasses the maximum junction temperature (t=0.15 s) after which the power module is permanently damaged.

B. Overrated Device Three-phase Faults

The tests with the rated device shows that the power module can provide 2.0 p.u of fault current, however, the initial junction temperature must be lower than 50 ºC, which is not a realistic constraint. To increase the fault contribution of the inverter, this work proposes to increase the current rating of the power module. As mentioned, the other components, including the grid filter remain at rated power. Fig. 5(e)-(f) show the experimental results with the overrated semiconductor when the inverter provides 2.0 p.u and 3.0 p.u of fault current. Fig. 6(e)-(f) shows their corresponding simulated thermal response. As seen, the better electrical and thermal characteristics of this device allow it to provide higher fault currents while keeping the device under a safety margin. This device can withstand 2.0 p.u of fault current with a maximum $\Delta T = 20$ °C, and 3.0 p.u with a maximum $\Delta T = 40$ °C. This means that the inverter with this larger semiconductor can provide high fault current even when the initial junction temperature is as high as 100 °C.

C. *Fuse-Relay Coordination Islanded Microgrid*

This section evaluates if the proposed inverter can provide enough fault current for sufficient time to maintain the fuse-relay coordination in the test system of Fig. 1. The coordination study is divided in I) fuse-blowing scheme II) primary backup coordination and III) backup relay coordination.

Table 2 summarizes the tripping times for the following tests.

Table II. Fuse-Relay Coordination Tests

Fault Current (p.u)	Test I Fuse melting time (s)	Test II Trip time primary relay (s)	Test III Trip time backup relay(s)
1.25	>10	>10	>10
2.0	9.67	>10	>10
3.0	0.508	1.1	2.47

These tests shows that a short-circuit fault of 1.25 p.u (typical for DERs) is not sufficient to blow the fuse or to trip the backup protection. For 2.0 p.u currents, the fuse takes a very long time to melt (9.7s). This result shows that the rated device will not be able to blow the fuse even if it can provide 2.0 p.u of fault current. Finally, at 3.0 p.u, the fuse melts rapidly in 0.5 seconds. Fig. 7 shows the fault current recorded by the SEL 651 which captured the overcurrent event and the clearing time for the fuse meting test. Notice that currents contain harmonics due to the saturation of the inductive grid filter core. The presented tests demonstrate that the proposed design maintains high-current for sufficient time to enable the fuse-relay and relay-relay coordination, which is promising step in the direction of enabling overcurrent protection for islanded microgrids.

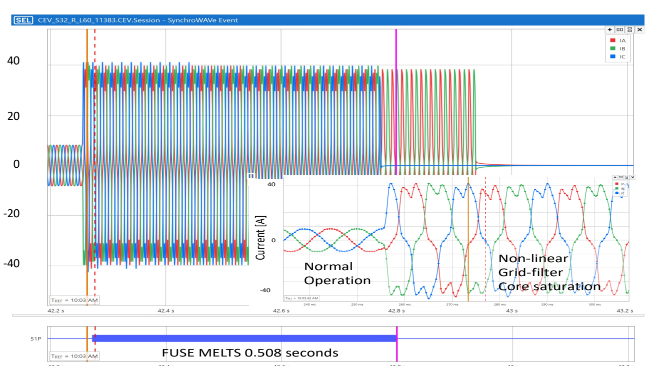


Fig. 7. Event file from SEL 651 (128 samples) which captured the overcurrent event and the clearing time of the fuse (0.508s).

V. CONCLUSION

This paper proposes modifications to enable three-phase inverters to provide high fault-current contribution during three-phase faults. The proposed design significantly increases the short-circuit fault contribution for enough time to enable fuse-relay and relay-to-relay coordination. This work presents preliminary results that show that few hardware modifications are required in the inverter to enhance its short-current contribution. This represents an important a step towards enabling the use legacy distribution overcurrent protection for protecting inverter-based microgrids.

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