A DC link-based approach to realize zero feed-in under both static and dynamic power system events

A. Paspatis, B. Adebisi
Dept. of Engineering
Manchester Metropolitan University
Manchester, United Kingdom
a.paspatis@mmu.ac.uk

G. Orfanoudakis, K. Siderakis, E. Karapidakis
Dept. of Electrical and Computer Engineering
Hellenic Mediterranean University
Heraklion, Greece
gorfas@hmu.gr

Nikos Hatziargyriou
School of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece
nh@power.ece.ntua.gr

***Abstract*—Two factors significantly limiting the increased interconnection of distributed energy resources in distribution systems are related with the thermal and the short-circuit limits of the primary substations. Even though the zero feed-in approach can address the limitations originating from the thermal limits, the short-circuit limitation issue can not be tackled by this solution. Hence, the short-circuit limitation of primary substations has evolved as the most critical limiting factor in further increasing the distributed energy resources in the distribution system. To address this issue, a novel solution is proposed in this paper, through a DC-link topology that can maintain the zero feed-in conditions of distributed energy resources, during both static and dynamic power system events. The proposed solution is thoroughly described, validated and compared with the conventional zero feed-in approach through simulations in MATLAB/Simulink. It is shown that it can inherently achieve zero current injection to the grid under a short-circuit, while it offers several other advantages, such as fault ride-through and immunity to several grid voltage disturbances.**

***Index Terms*—Distributed energy resources, net-metering, grid faults, power system, primary substations, hosting capacity**

I. Introduction

The ongoing progress towards sustainable generation of electricity has led to a massive increase in the penetration level of renewable energy sources (RES) in electric power systems over the previous years. Apart from the high-power RES plants, usually directly connected to the transmission system, the installation of such generation units at the distribution system is also attracting great attention from the users, the industry, and the policy makers [1], as it can efficiently utilize diverse areas and address spatial limitations.

The increased interconnection of RES has however posed technical challenges in the operation of power systems. To name a few, protection coordination, voltage regulation and power quality topics require special attention due to this undergoing transformation, with some of the related issues planned to be addressed through the smart grid concept [2]. In particular, regarding the installation of RES plants at the distribution system, significant limitations arise from the thermal and short circuit level limitations of the nearby primary substations [3], [4]. These limitations come from the maximum thermal capability of the equipment of the substations under normal conditions (e.g. the rating of the transformers), as well as from the short circuit current limitation under faults (e.g. the maximum current of the circuit breakers) [3], [4].

To avoid magnifying the issues faced by the power system operators, the net metering [5] scheme has been successfully introduced in most of the countries, where the RES plants at the distribution system are not flexible with regards to selling electricity to the network, but rather produce the electricity enough to cover local consumer energy needs. This scheme simply corresponds to a financial tool, charging for electricity usage through a vector summation of the energy produced and consumed for a given time period. Nevertheless, the RES plants still inject power to the grid, thus limiting the benefits of this approach, as they still need to abide by the thermal and short circuit levels of the closest primary substation. To improve the efficacy of the net metering scheme, the zero feed-in (or zero-export, or export-limiting) approach has been introduced [6], [7], where power is not allowed to be injected the grid, or is limited to specific amounts. Thus, the consumer is restricted to utilizing the power generated by RES exactly at its actual production time, or alternatively use energy storage devices.

The zero feed-in scheme is currently implemented based on power sensors (on the RES and load) and controllers that command the RES grid-tied inverters to curtail their output when the local load demands less power, so that no

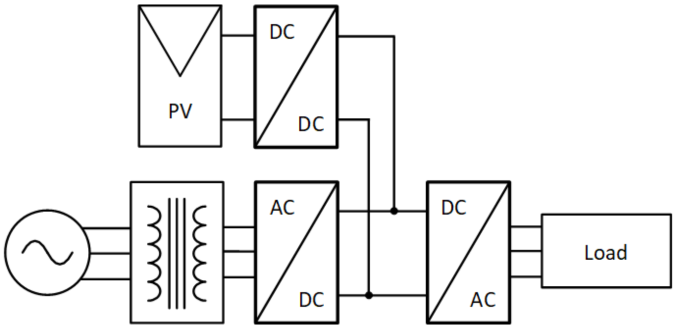


Fig. 1. The proposed topology.

power is injected to the grid. Controllers for this scheme have already been brought to the market [8], while advanced schemes to dynamically define relevant limits have recently been investigated [6], [7], [9]–[11]. However, the conventional zero feed-in/export-limiting approach is a steady-state tool that cannot handle transient effects, and thus cannot guarantee that the RES will not contribute towards the short circuit current of nearby primary substations.

In this regard, a need arises for a scheme that can maintain zero power injection to the grid, even during grid faults. This need is especially pertinent for large industrial plants that wish to employ the zero feed-in scheme to reduce their high electrical energy bills, but the adjacent primary substation are saturated with regards to their limits for introducing new RES plants. In this paper, a power hardware-based approach based on a common DC-link configuration, is proposed to provide this capability. In the past, such DC-link-based approaches have been employed for energy routing [12], solid-state transformers [13], wind turbines [14], machinery control [15], as well as series voltage regulation applications [16]. Building on those concepts, the proposed configuration introduces a modification - a multipulse diode rectifier - that results in inherently providing zero feed-in under any grid conditions.

The rest of the paper is organized as follows. In Section II, an overview of the existing zero feed-in and net metering schemes is given. The proposed topology is presented and analysed in Section III, which is followed by its simulation verification in Section IV. A discussion follows in Section V, while the paper is concluded in Section VI.

II. Zero Feed-In and Net Metering

In this section, the widely used net-metering and zero feed-in approaches are presented, motivated by the regulatory framework of Greece.

- Conventional net metering: The conventional net metering approach is a financial tool where through the appropriate metering of load consumption and PV production at the customer's point of connection, the customer is only billed for the extra energy consumed, compared to that produced by their PV plant. However, as in fact power injection to the grid is met for many hours, and especially during the day time, that approach causes stress to the power system. As an example, in Greece, to minimize this stress, the time period of the billing has been recently reduced from yearly periods to monthly periods [5], in order to prevent customers from over sizing their PV plants and hence mainly acting as exporters of electric energy.
- Zero feed-in: To further minimize the stress imposed to the power system through the net metering installations, in the zero feed-in net metering, emphasis is given to avoid any power injection from the customer's PV plant to the grid. To achieve this, a power sensor is placed at the point of coupling, and when reverse power flow conditions arise, a corrective signal is sent to the controller of the PV plant, to reduce its power production accordingly [6]. As it is evident, this is an effective tool to eliminate the power injection to the grid in net metering installations, thus supporting the hosting capacity of the network. However, such a scheme only realizes the zero feed-in condition during the steady-state, hence the significant hosting capacity limitation raised by the short circuit level limits of the adjacent primary substations are not aided.

In this regard, a challenge arises in realizing zero feed-in conditions during grid faults and other disturbances, in order to guarantee zero current contribution, and therefore a zero contribution towards a violation of the local primary substation short circuit level.

III. The Proposed Topology

A. Power circuit

The proposed DC-link topology to realize zero feed-in at all times is depicted in Fig. 1. In contrast to most of the already explored DC-link based configurations, where both back-to-back converters are fully controllable to support the different applications' requirements, the grid-side converter is proposed here to be a 12/18/24-pulse diode rectifier. Given that diode rectifiers intercept power flow towards the grid, the proposed configuration inherently offers zero feed-in under any grid conditions, including power system transient events. Furthermore, the RES, e.g. a PV system, is interfaced to the common DC link through a DC/DC converter, while the load is supplied by a fully controllable DC/AC converter (inverter).

B. Control principles

The load-side inverter in Fig. 1 operates in a grid-forming manner [17], providing tight voltage and frequency regulation to the load. Besides, the DC/DC converter is controlled to perform Maximum Power Point Tracking (MPPT) to the PV array, unless the generated power exceeds the power demanded by the load. Given that no power can be injected to the grid, the excess power in this case will be stored in the DC-link capacitor (bank), increasing its voltage. Hence, a requirement for a droop control scheme [18] arises for the DC/DC converter to avoid DC-link overvoltage in this case. This droop control approach can be based on the DC-link voltage (which is

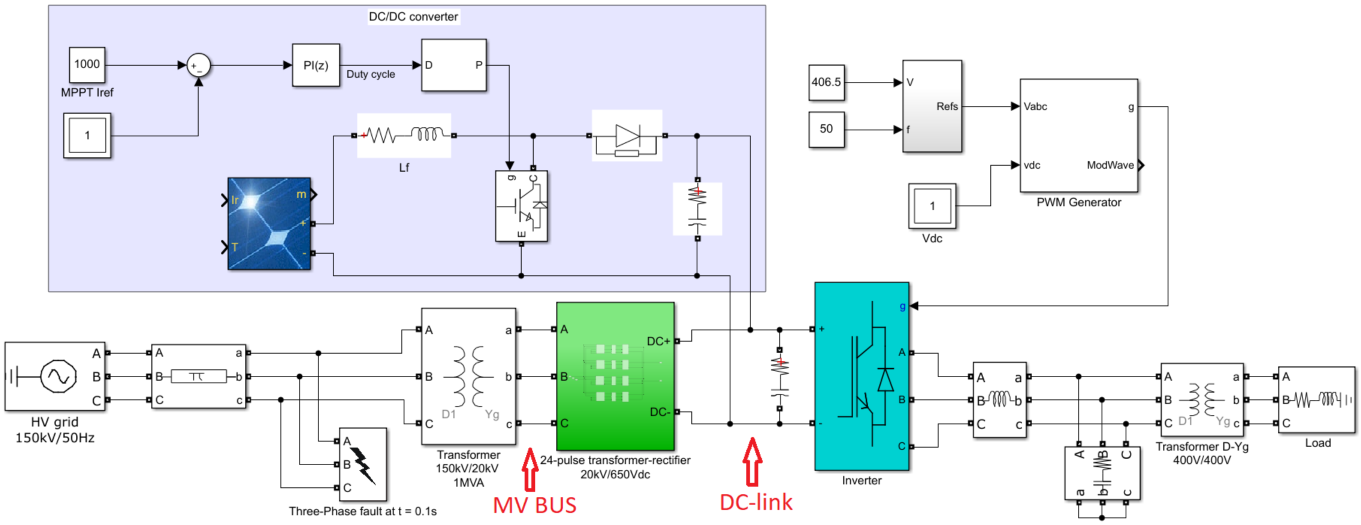


Fig. 2. The proposed system modeled in MATLAB/Simulink.

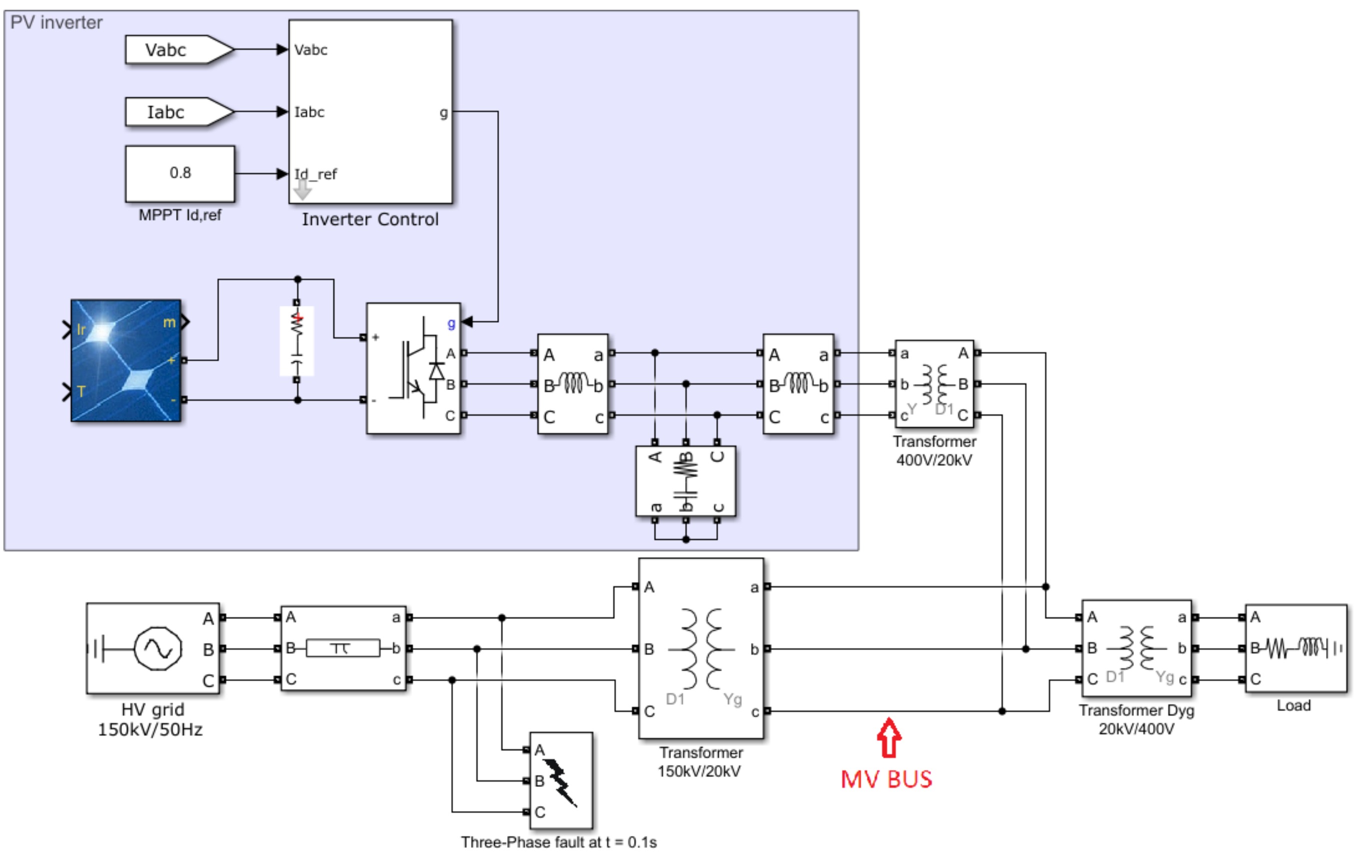
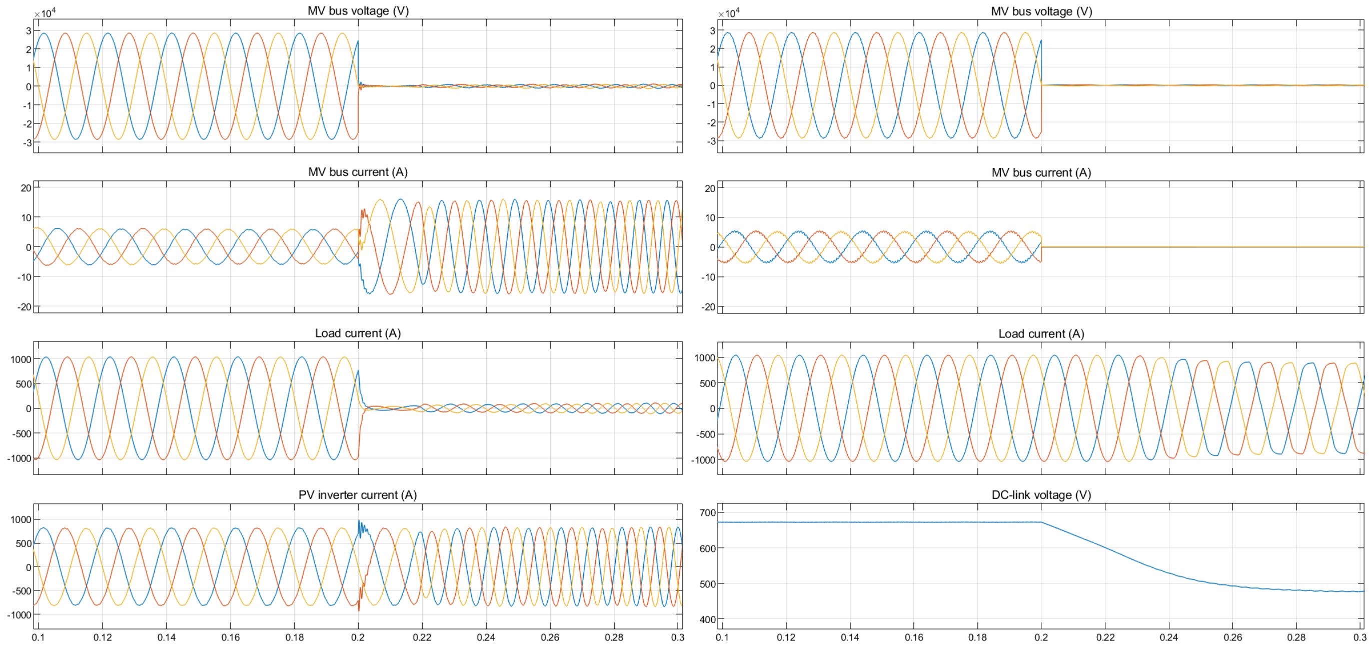


Fig. 3. The conventional system modeled in MATLAB/Simulink.



(a) (b)

Fig. 4. Comparative simulation results: (a) Conventional, (b) Proposed configuration.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
f	50 Hz	Load voltage	400 V
V_{PV}	400 V	DC-link capacitance	50 mF
Line length	50 km	Filter inductance	30 μH
Line resistance	0.01273 Ω/km	Filter capacitance	500 μF
Line inductance	0.9337 mH/km	Load	500+j100 kVA

measured anyway), thus simplifying the classical zero feed-in technique where power flow sensors are required to adjust/curtail the PV power production appropriately. Namely, as long as the DC-link voltage is close (e.g. up to 10%) above the nominal DC-link voltage, the proposed droop controller commands the DC/DC converter to regulate its input voltage-current so that the PV array operates at its MPP. Conversely, if the DC-link voltage rises above the specified threshold, the DC/DC converter is commanded to abandon the MPPT operation, and reduce the PV-side current so that the PV power is reduced to the level that matches the load power demand. The DC-link voltage then stabilizes to a safe (higher) level, while no power is provided by the grid under this condition, thus maximizing energy savings.

IV. Simulation Results

To validate the proposed DC-link-based zero feed-in approach, MATLAB/Simulink simulation results are presented in this section. A model of the proposed converter and system is shown in Fig. 2. The converter consists of a) a 24-pulse transformer-rectifier, rated at 1MVA with a 20kV input and 650V output, b) a Boost DC/DC converter, and c) a load-side inverter with an LC filter and isolation transformer (to suppress PV ground leakage currents and provide a neutral connection to the load). As discussed previously, the 24-pulse rectifier interfaces the MV bus with the common DC link, the DC/DC converter interfaces the PV array to the DC-link, and the load-side inverter supplies the load. It is noted, that in practice the Boost converter may consist of parallel or interleaved Boost modules, due to the high currents involved. The model also includes a fundamental version of the required controllers. Namely, the input (PV array) current of the DC/DC Boost converter is controlled by a PI controller, whose reference (Iref) is herein set to 1000A. As explained in Section III-B, this reference comes from either the MPPT algorithm or the droop controller. Also, the PV array voltage is set to 400V in the model, resulting in the DC/DC converter supplying 400kW to the DC bus (neglecting its losses). Besides, the load-side, grid-forming inverter controller simply consists of a three-phase sine wave voltage reference generator (including 3rd harmonic injection) and a PWM modulator. The reference generator is commanded to output voltage references with an RMS value of slightly more than 400V, to compensate for the LC filter and isolation transformer voltage drops, while the modulator generates PWM gating signals for the inverter based on the actual DC-link voltage.

Moreover, to highlight the advantage offered by the presented topology with regards to maintaining a zero feed-in condition during a power system fault, a comparison is performed with the standard steady-state zero feed-in net-metering configuration, shown in Fig. 3. In this configuration, the PV system and the load are directly connected to the MV bus via MV/LV transformers. The PV inverter is controlled according to the classic approach employing a Phase Locked Loop (PLL) for synchronization with the grid, and current controllers operating at the synchronous reference frame (d-q). The (normalized) reference current amplitude comes from the MPPT algorithm, and is set to a value corresponding to 400kW (as in the proposed system), with a unity power factor. The main parameters for the two systems are presented in Table I.

In both cases, the system operates under the same load conditions of 500kW and 100kVar, when a grid fault happens close to the local primary substation, as can be seen in Fig. 4. When the grid fault occurs, at t = 0.2s in Fig. 4(a), it is observed that the customer is injecting current to the MV bus (2nd graph) thus contributing to the short circuit current of the local primary substation. Namely, the PV inverter, which is controlled to generate a certain value of RMS current, continues to feed this current to the MV bus. However, due to the collapse of the voltage during the fault, this current is not directed to the load, as normal. Instead, it is fed to the MV (20kV) side of the 150kV/20kV transformer in Fig. 3. This changes the phase and increases the magnitude of the current through this transformer, as before the fault the transformed carried current corresponding to 100kW, whereas during the fault it carries current with a peak value of approximately 16A, corresponding to 400kW at 20kV. It is noted that the increase in the frequency of the waveforms of Fig. 4(a) after the fault, is due to the loss of synchronization by the inverter's PLL, which is normally soon detected and trips the PV inverter.

On the other hand, as it can be observed through the second graph of Fig. 4(b), the proposed approach causes no current injection to the grid. This is ensured by the diode rectifier employed at the grid side of the proposed topology. The bottom two graphs of Fig. 4(b) illustrate the drop of the DC-link voltage following the grid fault, and the inability of the load-side inverter to feed the load with the required power. If the fault is sustained, this eventually leads to tripping the load-side inverter. However, if the fault is cleared within a few tens of milliseconds, the proposed topology can restore its operation, advantageously providing fault ride-through.

V. Discussion

The proposed topology, can integrate the customer's load and PV system to the distribution system, ensuring both the provision of electricity in a sustainable manner, as well as the absence of power injection to the grid, thus alleviating the strict limitations for the installation of PV systems. In particular, the proposed approach can guarantee the elimination of the contribution to the thermal level and short circuit level stress of the local primary substations. Furthermore, in the case of a sustained short-circuit or grid voltage interruption, the proposed topology can maintain power provision to the load if the PV production matches or exceeds the required power. But even if the PV power is lower than the demand, the energy stored in the DC-bus of the proposed topology can advantageously provide Voltage Sag Ride-Through, that is maintain supply to the load until the grid voltage is reinstated. For the continuation of electricity provision, a battery system could also be considered, effectively forming an islanded microgrid, a topic which however is out of the scope of the present study. In addition to the above, the proposed configuration offers further advantages as compared to the conventional zero feed-in approach, namely immunity to several grid voltage disturbances due to the lack of a synchronization algorithm (i.e., a PLL), as well as inherent anti-islanding, since its rectifier diodes no not allow the flow of current in the absence of grid voltage (apart from their reverse leakage current).

On the other hand, even though the proposed approach was fundamentally verified in this paper, there are technical aspects relating to possible points of failure and abnormal conditions, that can affect the system operation. Particularly, component failures, communication issues, or compatibility issues with accompanying infrastructure may arise in the practical realisation of the topology. Additionally, although this study showed that the proposed topology contributes zero current in the event of a short circuit, its operation under other dynamic power system events and disturbances needs to be verified, as well. More specifically, the topology is expected to operate normally under the presence of (i.e., exhibit immunity to) voltage harmonics, notches, as well as frequency fluctuations. Over-voltages and voltage swells, on the other hand, which will result in increment of the DC-link voltage, may cause temporary reduction of PV power generation, due to the droop characteristic discussed in Section III-B. Besides, voltage sags, undervoltages and interruptions can lead to load-side inverter over-modulation and voltage distortion, while grid voltage imbalance can cause uneven current distribution to the multipulse transformer windings and DC-link voltage ripple. Finally, grid voltage transients may cause breakdown to the rectifier diodes, which must therefore be appropriately selected and protected.

Finally, given that the proposed configuration requires non-standard power components (multipulse transformer-rectifier, DC/DC converter, grid-forming inverter, isolation transformer) its scalability and cost-effectiveness need to be studied further for investigating its market potential. It is noted, however, that the PV inverters employed by the conventional approach also consist of DC/DC converters (to provide independent MPPTs) and three-phase inverters, hence their cost can be comparable to that of the DC/DC converter and load-side inverter.

VI. Conclusion

The main factors that affect the installation of new RES at the distribution systems are related with the thermal and short-circuit level limits of the adjacent primary substations. Even though zero feed-in net metering can alleviate the limitations originating from the thermal limits, the short-circuit level limitation is not tackled by this solution. Hence, the short-circuit limitation of primary substations has evolved as the most critical limiting factor in the further increase of distributed energy resources in the distribution system. Motivated by DC-bus solutions in other smart grid aspects, a novel solution was proposed in this paper, through a DC-link topology that can maintain the zero feed-in conditions of distributed energy resources during both normal and faulty grid conditions. The proposed solution has been validated through simulation results in MATLAB/Simulink. As compared to the conventional approach, apart from its superiority with regards to short-circuit current contribution, it offers several other significant advantages, namely fault/voltage sag ride-through capabilities, immunity to several types of disturbances due to not requiring a PLL, and inherent anti-islanding.

Future research will focus on the techno-economic evaluation of the proposed approach, towards application in industrial clients, the experimental validation considering all possible points of failure, and specifically the investigation of the grounding system in the load-side of the grid-forming inverter.

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