Renewable and Sustainable Energy Reviews 203 (2024) 114742

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review of multiport power converters for distribution network applications

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ARTICLE INFO

Keywords:
Multiport power converter
Distribution network
Low-carbon building
Microgrid
Renewable energy source
Energy storage system
Electric vehicle

ABSTRACT

Multiport power converters integrate three or more energy devices into a single (potentially highly controllable and efficient) hub. These characteristics suggest that multiport power converters may be valuable for the decarbonisation of distribution networks, where the increase of converter-interfaced devices has degraded system reliability and efficiency. This review analyses the suitability of a wide range of multiport power converter solutions for four example distribution network applications (where previous studies have focussed on a limited range of topologies or applications) and the research areas that can progress their maturity. A review of grid codes and standards overviews the base capability that multiport power converters are likely to require, some of which are carried forward as requirements for a novel comparison tool. The comparison tool is developed to qualify and score reviewed topologies in terms of a range of features that are weighted for the applications. Isolated and partially-isolated topologies perform well due to their flexibility to be configured for the specifications and their operational capabilities (including modularity and voltage decoupling). Further research should focus on the complex control interactions between ports and scaling of these topologies for medium voltages. In contrast, many direct current non-isolated topologies do not qualify due to their low flexibility to be configured for the applications. This suggests that future research could focus on the development of a more flexible non-isolated multiport power converter configuration to take advantage of the high efficiency and low footprint that these topologies might otherwise offer for low voltage applications.

Abbreviations

AC	Alternating current	MVG	Maximum voltage gain
BD	Bidirectional	N	Number of ports
C	Class	PFC	Power-factor correction
CLL/LLC	Capacitor-inductor-inductor/Inductor-inductor-capacitor	PSFB	Phase shifted full-bridge
		PV	Photovoltaic
D/M/MM/TAB	Dual/Multi/Modular multi-/Triple active bridge	PWM	Pulse-width-modulation
		RES	Renewable energy source
D/MT	Dual/Multi-transformer	RESO	Resonance
DC	Direct current	SCAL	Scalability
DN	Distribution network	TC	Transformer cores
(E)SOP	(Enhanced) Soft-open point	TM	Technology maturity

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https://doi.org/10.1016/j.rser.2024.114742
Received 12 January 2024; Received in revised form 22 May 2024; Accepted 8 July 2024
Available online 13 July 2024

(continued)

ESS	Energy storage system	UPFC	Unified Power Flow Controller
ISO	Isolated	UPQC	Unified Power Quality Conditioner
L/M/ULV	Low/Medium/Ultra-low voltage		
MF	Medium frequency	UPS	Uninterruptible power supply
MOD	Modularity	VD	Voltage decoupling
MPC	Multiport power converter	VSC	Voltage source converter

1. Introduction

The ongoing climate emergency and required decarbonisation is driving an increase in the penetration of power converter-interfaced devices on electric power systems [1]. This increase in power converters is subjecting low voltage (LV) and medium voltage (MV) distribution networks to several issues, as well as some new opportunities.

There is a large increase of renewable energy sources (RESs) on distribution networks (DNs) [2]. The low carbon generators are not being utilised optimally due to their low correlation (and uncontrollability) with respect to demand profiles, particularly on radial feeders that can experience significant voltage variations during generation-demand imbalance [3,4]. Enhanced soft-open-points (ESOPs) have been discussed to mitigate this issue and increase low carbon utilisation by interconnecting neighbouring radial feeders, along with any collocated RESs or energy storage systems (ESSs), to enable peak shaving and other grid support functionality [5].

In parallel with the increase of RESs there is an increase of Direct Current (DC) devices such as ESSs and electric vehicle chargers, all of which require conversion stages [6]. These conversion stages affect system costs, space-requirements, and efficiencies. However, the high number of energy sources and sinks also offer the potential for energy aggregation. Residential and facility buildings are examples of these high converter density scenarios that could benefit from the more efficient integration of energy devices with optimised energy utilisation.

While there are several issues relating to converter integration to established power systems, a large portion of the developing world remains without access to electricity [7], which can be linked to their constraint in terms of key social-development indices [8]. Some of these communities have the potential to be electrified by RES-based microgrids [9,10]. Technical features that impact the success of remote microgrids include: the reliability of components and the ability of the system to adapt as the community's needs vary [11].

Multiport power converters (MPCs) offer a solution to integrate multiple energy ports into a single aggregated hub [12]. An illustrative example of a MPC that interfaces six ports (three DC and three

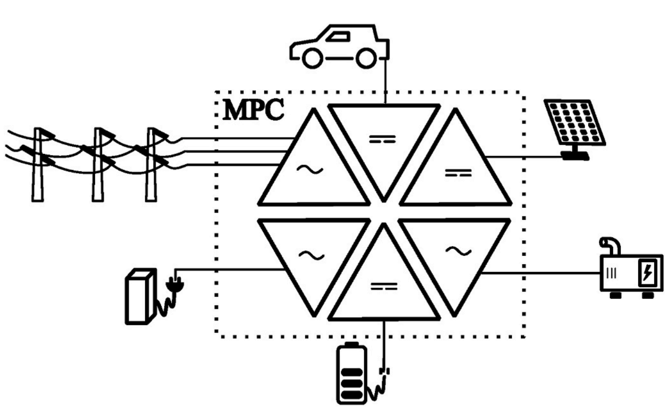

Fig. 1. Illustrative example of a multiport power converter (MPC) solution for an example six port application.

Alternating Current (AC)) is pictured in Fig. 1. MPCs are highly controllable, which offers effective energy management across all of their ports while maintaining local requirements such as power quality and grid stability [13,14]. These characteristics suggest that MPCs may offer valuable solutions to the DN issues with a reduced number of conversion stages compared to conventional AC and DC multi-terminal converter solutions, which may translate to a higher cost-efficiency and power density [15–17].

MPCs have been studied to improve the cost-efficiency of LV applications such as the integration of converter interfaced devices in residential buildings [15,18]. However, more advanced topologies with greater functionality and the ability to integrate a wider range of voltages are also being explored [19]. Several reviews of MPCs for these different applications exist but they often focus on individual applications (e.g. Refs. [20–23]) or individual topology families (e.g. Refs. [13,24,25,26]). Furthermore, most reviews fail to make a quantitative comparison. This study aims to offer a fundamental overview of the characteristics that MPCs will be required to possess and the features that make different topologies suitable for low and medium voltage applications. The wide comparison is implemented to identify research paths for the advancement of MPC maturity. A quantitative comparison tool is developed to enable meaningful comparison of the widely different topologies for four specific applications. Such an approach has not previously been achieved, as shown by Table 1, which overviews the existing works and their relation to the different contributions of this review.

The main contributions of this review are:

- An outline of the fundamental technical and safety requirements that MPCs are expected to be subject to and hence the baseline capability they will need to possess for DN applications.
  - o Suggestions are also made for the potential configuration of MPC standards considering their significantly different operating principles compared to conventional converter devices.
- A review of the features of a wide range of MPC topologies including considerations for MV applications.
- The development of a high-level Pugh Matrix comparison tool to identify the suitability of the reviewed MPC topology characteristics for a set of DN applications.
- The identification of future research pathways to develop the maturity of MPCs for these DN applications.

2. Grid codes and requirements for multiport power converters

An overview of grid codes, technical, and safety standards relevant to the design and operation of LV and MV MPCs is presented here to identify the baseline capability that they will be expected to possess. The requirements for the converter-interfaced devices that will be integrated by MPCs are discussed as there are no existing MPC standards. The key requirements identified in this Section will be carried forward for the assessment of suitable MPC topologies.

2.1. Review of grid codes and standards

Safety standards for a range of LV and MV converters and electrical equipment [27–32] define the range of hazards and the conditions of

Table 1
Overview of MPC research with respect to the objectives of this review.

Ref	Application(s)	Topologies	Review of standards	Topology assessment framework
[20]	Integration of LV loads, generation, and storage	Hybrid (derived) converters	No	Compare efficiencies and voltage gain for single application
[21]	Integration of solar PV and ESS to LV AC DN	Non-isolated MPCs	No	Compare leakage ground current and DC ripple for single case
[22]	Integration of solar PV and ESS to LV AC DN	DC MPCs	No	Describe necessary power flows and general features of topologies for single application
[23]	Integration of LV loads, generation, and storage	Hybrid (derived) converters	No	N/a
[13]	Multi-DC to AC applications at different voltage levels	Single-stage multi-DC to AC MPCs	No	Detailed qualitative discussion of MPC characteristics for several applications
[14]	Integration of multiple energy sources	MPCs	No	Discussion of key features but no analysis of suitability
[24]	Integration of RESs	Non-isolated DC MPCs	No	Discussion of required power flows and comparison in terms of component count, complexity, and efficiency
[25]	RES-based microgrids	Partially-isolated DC MPCs	Briefly	Comparison in terms of component count, functional capability, power and voltage levels, and efficiency
This review	Converter integration on LV and MV DNs	All MPCs	Yes	High level Pugh Matrix comparison of key features for four specific applications

operation that the hazards must be avoided in. Particularly relevant to MPCs is the information relating to equipment with multiple sources of supply [27–29]. These devices are required to ensure that neither the incorrect plugging of supplies nor the operation during normal or single faulted conditions result in hazards due to the multiple sources. Some design considerations are also introduced, including: the prevention of voltage back-feed (which can be achieved using isolation), protection against unintentional islanding, potentially high touch current levels due to the passing of energy between sources, and damage to wiring.

For the connection to AC DNs, grid codes historically required the provision of basic functionality to maintain the grid's satisfactory operation, such as power factor control [33,34], power quality requirements [34,35], and grounding requirements [36,37]. However, DN requirements increasingly include advanced functionality, such as reactive current support [38,39], active power injections for frequency support [34,40], and the definition of islanded capabilities [37,41]. MPCs will likely need to possess all of this functionality due to their key role for grid support and as an integration hub for multiple energy sources and sinks.

AC grid connection requirements are framed in terms of the minimum capability of the given energy source, which enables the system operator to have some confidence that the device will maintain acceptable operation throughout its lifetime. Most prosumer devices (such as ESSs [34], interconnectors [42,43], and bi-directional EVs [44]) are also treated in this way, which is thought to fail to effectively describe their time-varying power flows [45]. Consideration will need to be made for the configuration of requirements for MPCs, which will interface multiple energy sources to potentially multiple networks, and whose minimum capability will be difficult to define.

As well as meeting AC DN requirements, MPCs will need to simultaneously maintain the operation of its other ports, similar to a DC collection pool or microgrid [42,45]. These DC network requirements are less widely defined, although an overview is provided in Ref. [45]. The review describes functional requirements including: sufficient DC capacitance, electromagnetic compatibility [46,47], voltage ripple [48], and hold-up time (the period that a DC network should maintain supply to local loads) [49] following a disturbance. The review [45] also highlights the safety standard for LV DC distribution systems [32], which requires galvanic isolation of the high overcurrent and voltage AC DN side from lower current and voltage DC ports. Although other examples of an explicit requirement for converters to achieve galvanic isolation were rare (only the Ecuadorian grid code for solar PV less than 100 kW [50]), a similar need to isolate high overcurrent ports may be necessary in MPCs.

2.2. Considerations for MPCs

Some suggestions are made here for the configuration of grid code and safety standards for MPCs considering the review in Section 2.1. Each port will need to meet the standard safety specifications corresponding to its given energy source or sink, as well as making additional efforts to ensure that new hazards are not introduced due to the operation of the other ports. Specific protective procedures will need to be taken between ports with different voltage and current properties, which may resemble the protection zones for DC distribution networks detailed in Ref. [32]. Assuming that the MPC is designed to meet these safety requirements, operational capabilities will need to ensure: 1) the effective operation of the MPC to maintain controllable energy flow and 2) the meeting of grid connection agreements to ensure the MPC does not degrade the stability and power quality of any of the electrical power systems it is connected to. The former capabilities may be related to the DC collection pool requirements detailed in Ref. [45] while the latter will resemble conventional AC DN requirements. Although it will be difficult to define a minimum specification for the MPC at the AC DN connection point, it may be possible to define a minimum capability according to the aggregated energy capacity and characteristics of the

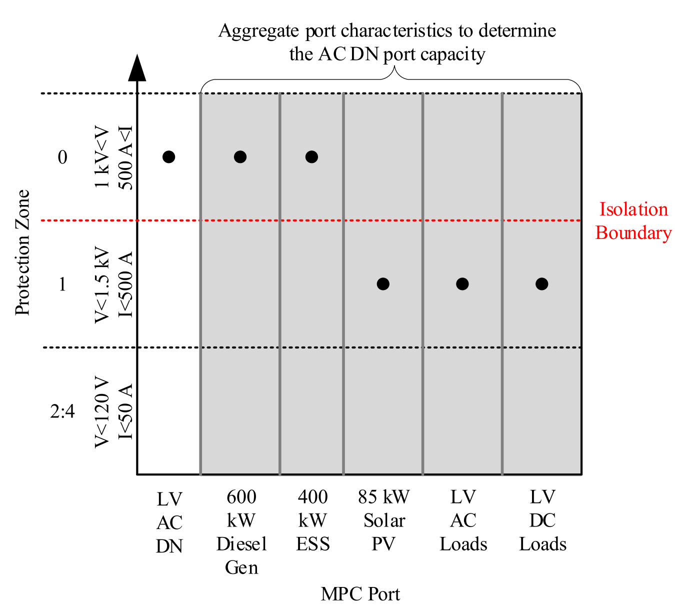

Fig. 2. Potential structure of grid code and safety standard requirements for MPCs with reference to the protection zones defined in Ref. [32].

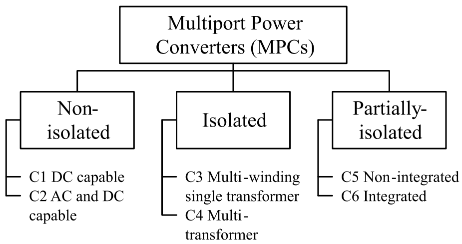

Fig. 3. Proposed MPC classification structure.

remaining ports (while also considering any other AC DN connected ports).

Fig. 2 depicts the potential MPC grid code and safety standard configuration for an example Facility Building Scenario (S3), which is described in detail in Section 4.1. The protection zones are derived from the standard NPR 9090 [32], which classified combined AC and DC installations (not exceeding 1500 V (DC)) according to their voltage, current, and power levels. The figure highlights the key point between Zones 0 and 1, across which ports must be galvanically isolated. The figure also indicates the definition of the AC DN port's minimum operational capability according to the aggregation of the remaining ports. Zones 2 to 4 are grouped in Fig. 2 due to their lower voltage and current properties that do not characterise any of the example ports. The protection zones and conditional isolation requirement will be carried forward for the qualification of topologies in the comparison methodology later in this review.

3. Multiport power converter topologies

This Section provides an overview of a wide range of existing MPCs that are relevant to DN applications. The literature review is organised according to a classification structure (pictured in Fig. 3) based on the topology of the MPC. Some of the reviews detailed in Table 1 utilise similar classification structures to ease the overviewing and comparison of topology features, however, an exclusive structure (so that all branches are distinct from one another) that encompasses such a wide range of topologies has not been proposed. The classification structure used here separates MPCs initially according to their galvanic isolation, either: non-isolated, where there is no isolation between any ports; isolated, where all ports are isolated from one another; or partially-isolated, where there is at least one isolated and one non-isolated conversion stage. An additional level of subclasses (C1 to C6) is introduced to further describe topologies and their general features, which are introduced and discussed throughout Sections 3.1 to 3.3. Additional considerations and examples of MPCs for medium and high voltage applications are discussed in Section 3.4. Selected topologies are pictured for each subclass, without specifying the source, load, or prosumer device that may be interfaced at each port (depending on the capability of the given conversion stage).

3.1. Non-isolated multiport power converters

The defining feature of non-isolated topologies is the complete lack of an isolating transformer. The configurations can often be simple compared to isolated topologies. Therefore, they can achieve high efficiencies and power densities for the applications they are designed for [22]. However, some of the simple configurations can lack bidirectional flexibility, constraining them to a low number of power flow modes [51], and can be difficult to adapt beyond the number and type of ports they are designed for. The configurations may also lack sufficient capabilities to safely integrate significantly different voltage levels due to the lack of galvanic isolation. Alternatively, multiport configurations of conventional independent converter solutions can be included in the non-isolated class, which offer high technological maturity, operational flexibility, and scalability for higher voltage levels but at the cost of lower power density and efficiency compared to integrated non-isolated solutions. Non-isolated MPCs can be further classified according to their ability to interface either only DC ports or both AC and DC ports without the use of additional conversion stages.

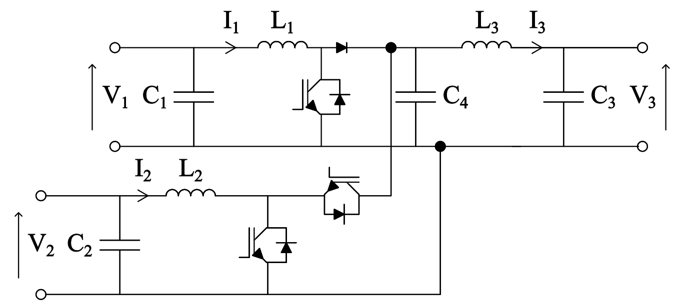

Fig. 4. Cascaded buck and bidirectional-boost converter [52].

3.1.1. DC capable

DC capable non-isolated MPCs are incapable of interfacing AC ports, however, are suggested to be adapted to do so using a cascaded inverter [22]. They are generally built from the interleaving of either simple (e.g. buck or boost) or more complex (e.g. half or full-bridge) fundamental converter cells. These topologies generally use the fewest number of active and passive devices to interface three DC ports and therefore achieve very high efficiencies for these applications.

Combined input/output DC converters mesh conventional converter cells, often with the objective of interfacing RESs and ESSs. An example is the combination of a unidirectional boost (to interface a PV port) with a bidirectional buck (to interface an ESS port) to a DC load (as pictured in Fig. 4) [52]. Magnetically or capacitively coupled converters adapt these cell combinations to achieve enhanced voltage boost. For example, two cascaded boost converters are linked using a coupling inductor in Ref. [53]. Resonance can be introduced to this topology by adding an active clamp, which enables soft-switching and the reduction of switching losses.

Examples of ultra-low voltage (ULV) three port converters are available on the market for integrated circuit telecoms applications [54, 55] and some LV residential or industrial instrumentation applications [56], however, these examples generally exhibit low bidirectional flexibility. Following the first generations, research has focussed on improving the number of components, efficiency, and operational flexibility of DC capable non-isolated topologies for three port applications [57–59].

3.1.2. DC and AC capable

DC and AC capable non-isolated topologies offer potential improvements in power density for applications that include AC ports, such as the interfacing of DC sources with DC and AC loads. Some configurations offer improved bidirectional flexibility compared to DC only non-isolated topologies, but this can come at the cost of more complex operation.

Derived converters, which hybridise conventional cells, were specifically developed to improve the efficiency of applications that serve DC and AC loads compared to multi-stage back-to-back converter configurations. An example, the Boost Derived Hybrid Converter [60], replaces the switch of a boost converter with a full-bridge cell. The configurations offer simple control, compact design, and reduced cost for their designed applications. Although derived converters have been proposed to be interlaced to achieve three phase output [61], or to use additional active and passive devices to increase the voltage gain [62], they do not appear to possess the flexibility to interface significantly different port numbers or types without additional conversion stages.

Reconfigurable-port topologies use relays and other slow switching

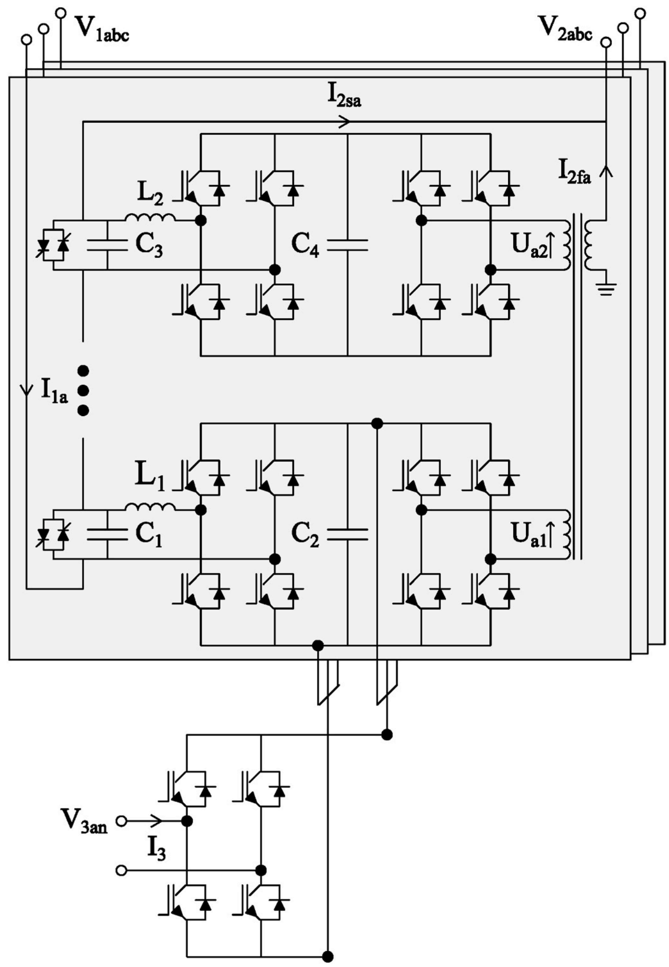

Fig. 5. Single- or multi-level multiport UPQC, derived from the MPC configuration in Ref. [70] and the multi-level configuration in Ref. [71]. The triple-dots indicate the potential scaling to multi-level.

devices to change the connection of standard converter cells and their ports. The simple construction leads to a low number of devices, which enables high efficiencies and power density. However, the slow switching devices can constrain the operational flexibility to transition between power flow modes. An example is the single-stage three-phase reconfigurable converter, which transitions from interfacing either a DC solar PV or ESS to the AC grid, or to each other [63].

An additional example of a DC and AC capable non-isolated MPC is the adapted Unified Power Quality Conditioner (UPQC) that integrates storage or distributed generation on the DC link of a conventional back-to-back voltage source converter (VSC) configuration (as pictured in Fig. 5) [64]. The multiport UPQC is developed from two-port UPQC topologies (otherwise known as the Unified Power Flow Controller (UPFC) [65,66] or Smart Power Bridge [67]) that interface the output of one VSC to the AC network via a series transformer and the other using a conventional parallel connection. UPQC-type converters are studied for distribution [64,65] and transmission network applications [65–68]. Although the configuration can include the use of transformers, it is classified as non-isolated as the transformers are not integrated within the converter topology. Topologies derived from conventional independent converters like the UPQC can benefit from the technological maturity, high controllability, and modularity of the independent converter solutions [69].

UPQC-type topologies were developed so that the series ports could control the AC line voltage and active power flow using a partially rated converter, while the parallel port could compensate the reactive power flow and regulate the bus voltages. Alternative configurations for single- [72,73] and three-phase applications [74] have been proposed, as well as configurations that replace the series connected transformer (which needs to withstand the AC line's short circuit current and possess a core with sufficient over-excitation tolerance) with three single-phase converters [67,75] or a single modular multilevel converter [64]. The UPQC MPCtopology is particularly interesting as it introduces the additional consideration of the series connection of the output port to the ACnetwork to achieve voltage control, which is different from the series-connection of submodules in multilevel topologies that makes them suitable to support high voltages (discussed in Section 4.2.6).

3.2. Isolated multiport power converters

Isolated MPCs use transformers to galvanically isolate every port from one another. As a result of this global isolation, isolated MPCs offer high fault tolerance and voltage gain [76]. Depending on the exact configuration they can offer: modularity, resonance, and simultaneous power transfer between different ports. However, they are non-linear multi-input multi-output systems that have a high degree of coupling between states, which can result in complex modelling, analysis, and control [77]. Compared to non-isolated topologies, isolated MPCs may be able to support an increased number of power flow modes and be more flexible to move between them, particularly when using bidirectional modules [19], but at the cost of lower efficiency, lower power density, and increased complexity. Isolated MPCs are further classified according to the number of windings and transformers that they utilise.

3.2.1. Multi-winding single transformer

Multi-winding single transformer isolated MPCs use a separate winding to interface each energy port through a single transformer core. Each winding possesses a DC-AC conversion module, which can result in a high number of active devices (increasing the number of potential points of failure). In general, multi-winding single transformer MPCs are further distinguished according to the resonant ability of their DC-AC conversion modules or based on the symmetry of the port bridge connections on either side of the transformer. Asymmetric configurations (with different bridge coupling on the primary versus secondary sides) offer the ability to reduce the number of switching devices (to reduce the cost and losses) but may only be suitable for specific applications [19].

Non-resonant topologies generally consist of dual active bridge (DAB) conversion modules, which offer effective control of the output voltage and power flow between multiple ports [78] due to their high degree of freedom compared to resonant modules. However, their switching frequency can be constrained by the inversely proportional relationship between the DAB's power transfer and inductance [79].

Resonant topologies are generally built from series resonant converter components (as pictured in Fig. 6), and can therefore support higher switching frequencies [79]. These topologies are described as being suited for applications where the load is highly variable and therefore requires output voltage regulation [19].

Multi-winding MPCs exhibit mid-level market maturity compared to other configurations, as some MW solutions are available on the market for ULV applications [80], while similar topologies are also beginning to be subject to more advanced testing in industrially relevant power and voltage conditions e.g. Ref. [81].

3.2.2. Multi-transformer

Single winding multi-transformer isolated MPCs continue to interface each energy port with its own winding, however, each input-output winding pair are connected through an independent transformer core. The multiple transformers increase the core material, volume, number of switches, and losses and reduce the fault tolerance (due to the inability to isolate and disconnect the faulty port winding) with respect to multi-winding configurations.

Dual-transformer triple active bridge (DT TAB) converters are a

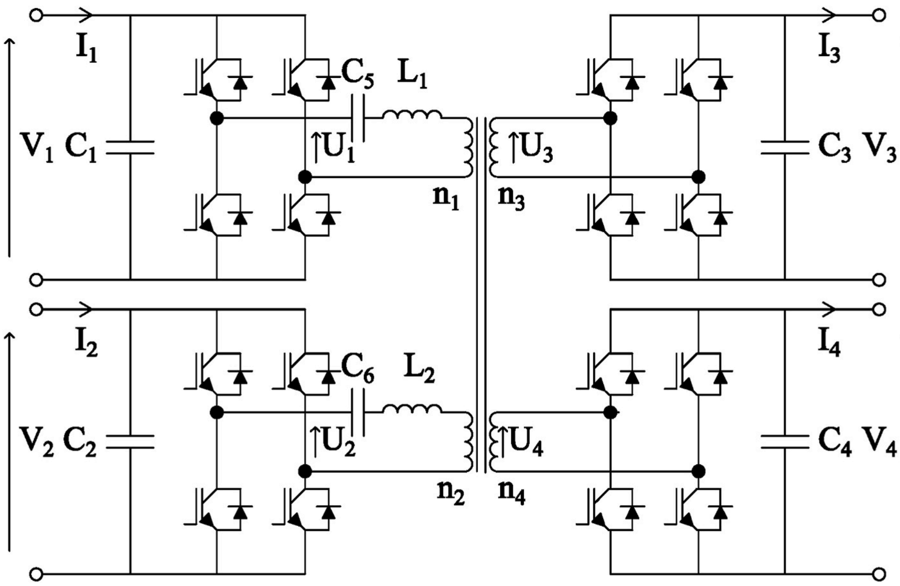

Fig. 6. Series resonant multi-active bridge (MAB) [79].

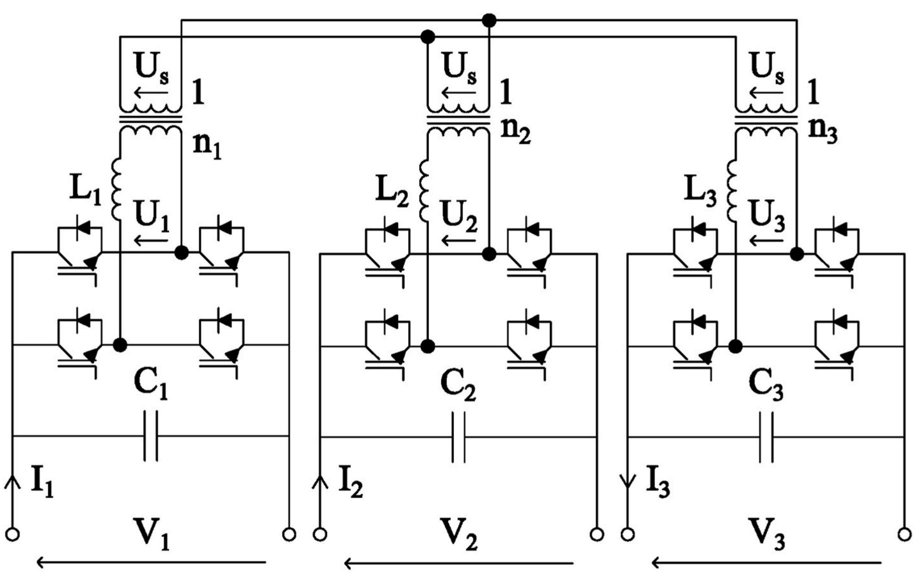

Fig. 7. Modular multi-transformer (MT) multi-active bridge (MAB) [86].

multi-transformer version of a TAB [82]. Proponents of the DT TAB suggest that it offers: reduced circulating current between ports, reduced transformer inrush current, improved lifetime, and reduced losses [83].

Modular multi-active bridge (MMAB) converters are a multi-transformer variant of the MAB, which can offer improved modularity due to their ability to interconnect standard modules. An example is pictured in Fig. 7. They can also offer improved scalability by varying the connection approach of each module [84]. MMABs have been shown to be at risk of high frequency oscillations, although hardware and control solutions have also been proposed to mitigate these issues [85].

Capacitor-inductor-inductor (CLL) resonant configurations are composed of two independent half-bridge CLL resonant converters, each interconnected to a single-phase bridge rectifier via their own independent transformer cores [87]. The dual-transformer CLL resonant converter offers soft switching and therefore a higher switching frequency, a wide range of input and output voltages, and a simple filter structure. The multiport CLL resonant converter is also shown to be capable of managing the power flows through a central controller without the need for communication devices between ports [87].

3.3. Partially-isolated multiport power converters

Partially isolated MPCs integrate three or more energy ports using at least two conversion stages. Typically, this involves incorporating one isolated and one non-isolated stage, but can include multiples of each. As a result, partially isolated MPCs can offer some of the benefits of both isolated and non-isolated MPCs. Partially isolated MPCs can offer high operational flexibility with highly controllable ports and can interface different voltage levels across the isolated stage. They can also use simple additive configurations to interface additional ports without significantly increasing the number of active or passive devices, which may offer more cost-effective solutions compared to fully-isolated topologies. Partially isolated MPCs are further classified according to the realisation of the isolation stage.

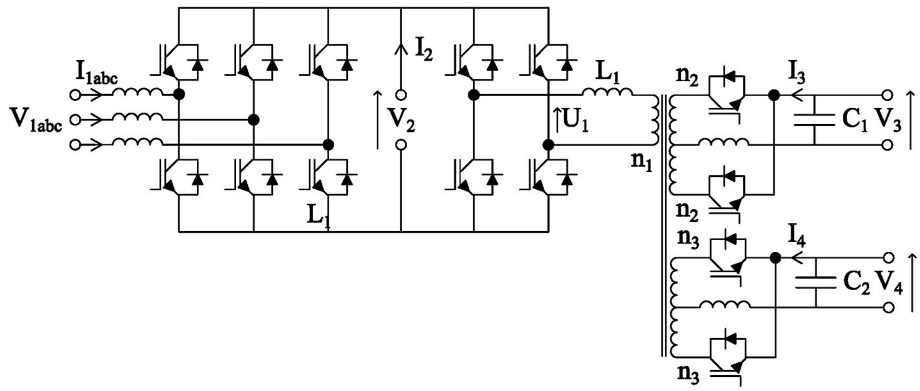

Fig. 8. Cascaded two-stage PFC and PSFB [91].

3.3.1. Non-integrated

Non-integrated partially isolated MPCs are formed by a cascaded connection of isolated and non-isolated topologies. This combination of established converters means that the configuration and control should not be significantly more complex than that of the independent conversion stages. Non-integrated solutions also offer good modularity, decoupled port voltages (with the use of shunt devices on non-isolated ports), and fault isolation across the transformer. However, the efficiency of these solutions can be reduced due to the cascaded conversion stages. Non-integrated partially isolated MPCs can also require a high DC link capacitance to minimise the interactions between the ports [88, 89] and will be subject to the impedance interaction between the cascaded converters.

The non-integrated partially isolated MPCs generally include a conventional two- or three-level VSC that interfaces an AC port with a DC port before achieving isolation and integrating additional ports using a DC-DC converter [90]. combines an isolated DAB DC-DC converter with a rectifier to interface two DC sources to the AC grid [91]. cascades a three-phase six-switch power factor correction (PFC) as the AC-DC stage with a phase shifted full-bridge (PSFB) as the DC-DC stage (as shown in Fig. 8). The interconnection of a three-phase three-level T-type PFC with a single winding multi-transformer type DC-DC converter that includes a full-bridge on the primary side and a buck on the secondary is proposed in Ref. [92] for battery charging applications. Additionally, a three-port converter solution that achieves galvanic isolation of the AC grid port from its two DC ports (PV and battery ESS) [93] appears to be one of the only MPC solutions available on the market that is explicitly designed for a DN application.

3.3.2. Integrated

Integrated partially isolated MPCs merge the isolation stage within the main topology, eliminating the need for cascaded converters. This approach enables integrated solutions to operate with a lower number of active devices and a reduced DC link capacitance compared to non-integrated solutions. However, the integration can result in complex configurations and controls that can be challenging to adapt modularly. In the case of interfacing only DC ports [94], proposes a MPC by integrating a bidirectional PWM converter and a series resonant converter. This integration reduces the number of semiconductors and enables the integration of magnetic components into a single magnetic element. Furthermore [95], presents a partially isolated MPC for EV batteries with automatic current balancing, interleaved PWM control, and enhanced transformer utilisation. In the case of interfacing AC and DC ports [96], considers a dual three-phase active bridge as a MPC by simultaneously accounting for the AC and DC ports on the primary side separately from the isolated AC and DC ports on the secondary side (pictured in Fig. 9) [97]. develops a three-phase single-stage isolated converter, which combines a three-phase PFC discontinuous-current-mode boost rectifier with an inductor-inductor-capacitor (LLC) resonant half-bridge converter and two additional switches. The usefulness of this MPC lies in its ability to achieve a tightly regulated isolated output voltage while enabling zero-voltage switching on the additional switches throughout the entire input and load range. There is one example of an integrated partially isolated MPC solution available on the market [98], however, its ULV configuration suggests it is not particularly relevant for DN applications.

3.4. Examples of multiport power converters for higher voltage applications

A MV application that may benefit from the use of MPCs is the enhanced SOP, which is described for this study in Section 4.1 as interfacing two MV AC ports (representing DN lines) to a LV DC port (for the integration of a RES or ESS). This application is suited to MPCsolutions that provide high voltage gain and isolation (to support the interfacing of different voltage levels) as well as being scalable (to support the large voltages of the MV ports).

[99] proposes a MPC for MV applications that connects two AC ports using a back-to-back multilevel converter composed of series connected

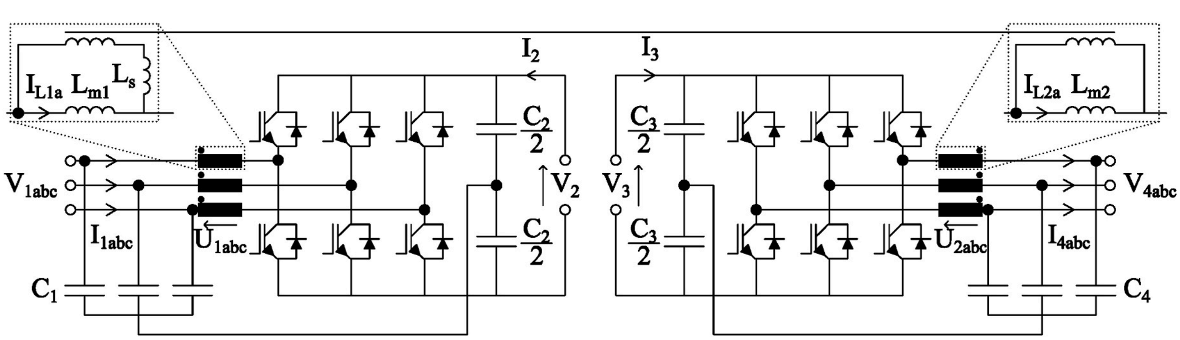

Fig. 9. Dual three-phase active bridge [96].

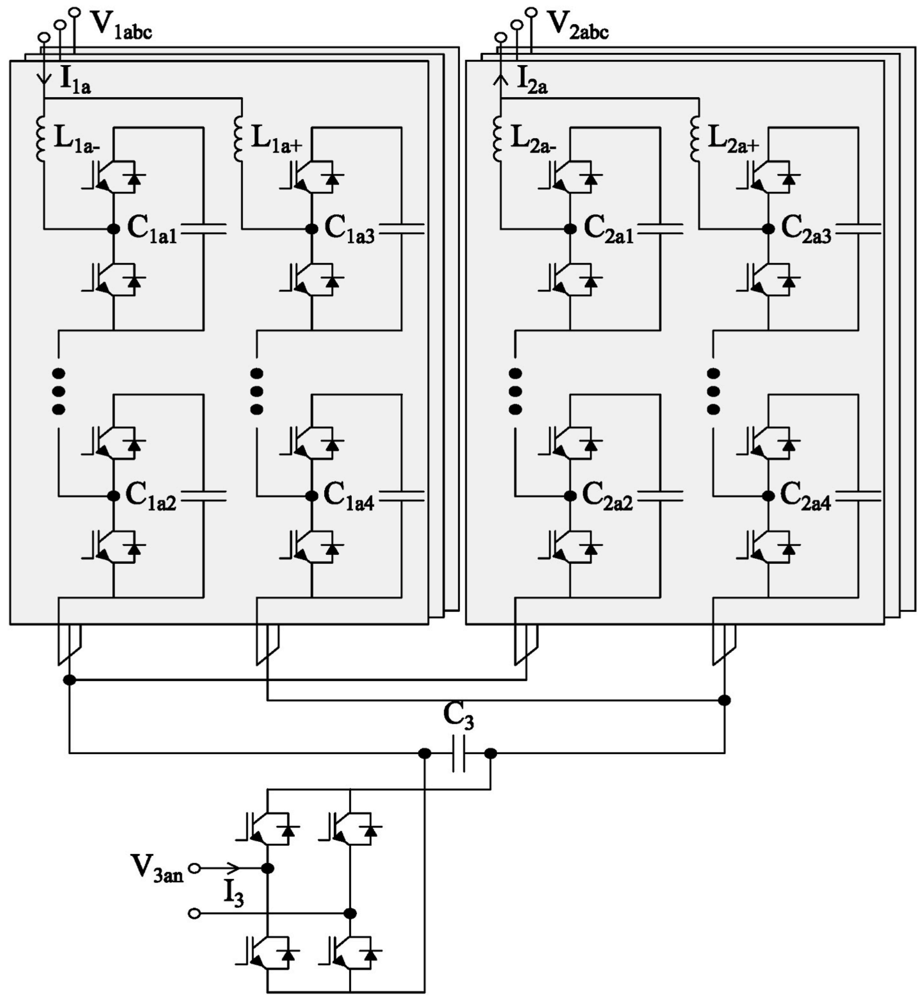

Fig. 10. Modular half-bridge-based converter [99]. The triple-dots indicate the potential scaling to multi-level.

half-bridge cells (pictured in Fig. 10). The converter becomes a MPC when the common DC link that decouples the AC ports integrates an additional energy port. The series connection of the submodule cells allows the generation of any AC voltage level. This half-bridge configuration would require an additional converter stage to interface a DC ESS or distributed generator and would therefore resemble a conventional multi-stage converter, however, a full-bridge configuration could control the DC voltage and therefore interface a DC port without additional stages.

[100] proposes an AC-AC-DC converter for MV applications that utilises a multi-winding medium frequency transformer (pictured in Fig. 11). The AC ports are interfaced to their windings across cascaded full-bridge cells and the DC port is interfaced using a single-phase AC-DC conversion stage. Additional resonant circuits and/or transformer solutions can be used to reduce the overload requirement of the transformer core. The AC circuit configuration is repeated for each phase.

[101] proposes a multilevel modular smart transformer that also integrates two MV AC ports with a DC port. The configuration uses a series connected cascaded half-bridge configuration that allows the interconnection of the AC ports to either side of a multilevel multi-winding multi-transformer-type DC-DC converter. One winding from the secondary side of each transformer core connects in parallel to contribute to the DC port. The DC-DC converter unit can take different forms, such as those described in Section 3.2), the choice of which is likely to be informed by the individual unit's characteristics.

A three-port UPFC is developed for high voltage transmission network applications in Ref. [102], which uses a modular multilevel shunt converter and two series connected converters to interface to the ultra-high voltage grid (the multilevel configuration pictured in Fig. 5). Two-port multilevel UPQCs for DN applications are also developed, which include: diode clamped [103], neutral-point clamped [104], and flying capacitor [105] converter approaches. Other studies are shown to implement either two-level [67,75] or modular multilevel converters [64] on the series side to remove the need for the series transformer in two-port applications.

4. Method for MPC topology comparison

An adapted Pugh Matrix method [106–108] is developed to compare the MPC topologies using the information collected throughout the literature review in Section 3. The comparison accounts for the variable importance of desirable features for different application scenarios. The scenarios represent specific configurations of the applications that MPCs are expected to support the electrical power system's decarbonisation. The method consists of four stages.

Firstly, each scenario is defined in terms of the critical qualifying features that are required to achieve the given function. These qualifying features are: the number of ports, the number of bidirectional ports, the number of AC, and the number of DC ports. Additionally, scenarios require the galvanic isolation of ports in Protection Zone 0 from any ports in Protection Zones 1–4, as defined for DC distribution networks in Refs. [32,45]. Protection Zones are determined according to the voltage and current characteristics of each port. Section 4.1 and Table 2 describe the four scenarios and their critical features that will be used to qualify

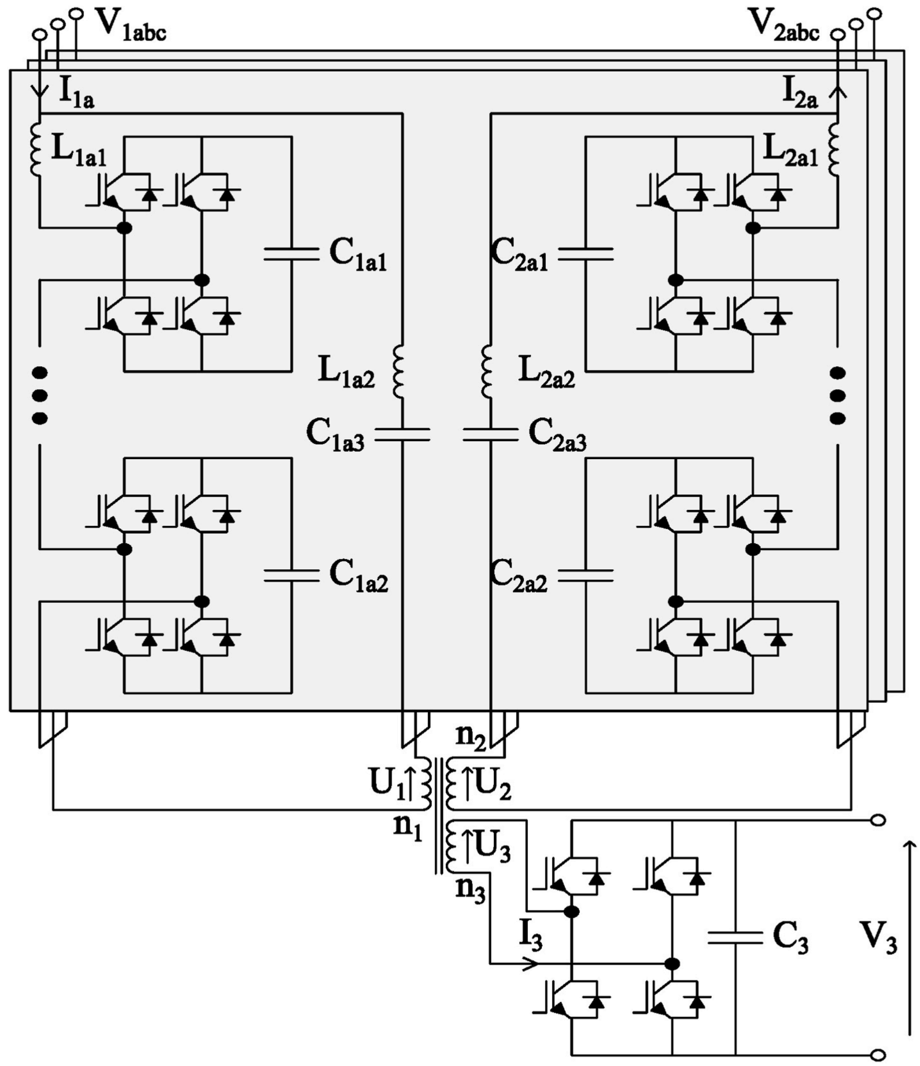

Fig. 11. Modular medium-frequency transformer-based converter [100]. The triple-dots indicate the potential scaling to multi-level.

Table 2
Application scenario specifications, including the qualifying port features.

	Scenario	Application	Qualifying (port) features				
			Total ports	Bi-directional ports	AC ports	DC ports	Isolated (Zone 0) ports
1	Enhanced SOP	2 × 20 kV 400 kVA DN feeders, 1 × 400 V 100 kW solar PV	3	2	2	1	0[a]
2	Residential Building	1 × 400 V 30 kVA DN feeder, 1 × 120 V 3.5 kW solar PV, 1 × 50 V 17.5 kW ESS, 1 × 250 V 7.4 kW EV charger	4	2*	1	3	0
3	Facility Building	1x 600 kVA AC DN, 1 × 400 kW UPS, 1 × 85 kW solar PV, AC and DC critical loads (~500 kW), 1x Diesel generator (600 kVA); all at ~400 V	6	2	3	3	3
4	Remote Community	1 × 240 V 20 kVA DN, 1 × 120 V 12 kW solar PV, 1 × 50 V 8 kW ESS + 1 × 20 kV 50 kVA future DN feeder	3 + 1	2 + 1	1 + 1	2	0 + 1

[a] indicates that no ports need to be isolated (according to the isolation requirement defined by Ref. [32]) as the MPC only interfaces ports in Protection Zone 0. * indicates the assumption that the EV port only charges and does not provide vehicle to grid services. + indicates a projected future port.

topologies.

The topologies' critical features are compared with the requirements in Table 2 to identify if they qualify for the given scenario. An additional feedback loop is included in this qualification procedure to allow topologies with an insufficient number of AC ports to use additional inverters or those that require isolation of Protection Zone 0 ports to use additional transformers to meet the requirements. This use of an inverter is stated as a common solution for DC-DC MPCs [22], as is the interfacing of a converter to the AC network via a transformer, and allows the assessment of the suitability of the full range of MPC topologies. The number of switches and passive devices recorded for each topology are increased by 12 and 3 per additional inverter, while a single transformer with 6 windings (passive components) are added for those that require isolation to meet the scenario specifications.

The weighting stage then defines the importance of the non-critical but desirable MPC features for the given application. A weight from 0 to 3 is applied to each feature, where a weight of 0 signifies that the feature has no importance and a weight of 3 signifies that the feature is

Table 3
Weighting of desirable features for the MPC application scenarios defined in Table 2.

Feature	Weight			
	S1	S2	S3	S4
Maximum voltage gain	3	1	1	2
Galvanic isolation	3	1	0	2
Voltage decoupling	2	2	2	2
Resonance	1	1	1	1
Modularity	1	1	1	3
Scalability	2	0	0	1
Number of switches	2	2	2	2
Number of passive devices	2	2	2	2
Number of transformer cores	2	2	2	2

The features and their weights for each Scenario (S1 to S4) are shown in Table 3, which are justified in the following subsections.

very important for the given application. It should be noted that any scenarios that do not require isolation between two ports (according to the interfacing of Protection Zone 0 with Zones 1+) can receive a score if isolation is deemed to be beneficial for the application. The features, their weights, and the justification of these weights for different applications are described in Section 4.2.

The desirable features of each topology, which are identified throughout the literature review in Section 3, are assigned a normalised score between 0 and 1. These scores are then multiplied with their corresponding feature weights. The sum of these products describes a topology's suitability for the given applications. The contribution of each feature towards a topology's overall score can also indicate areas that different topologies are strong or weak in and where research efforts should be focused.

4.1. Study case scenarios

The study case scenarios represent example DN applications that MPCs are deemed to be able to provide significant benefit to, as outlined in Section 1 and detailed in Table 2. An ESOP case (S1) is derived from a monitored location in the DN operated by Spanish distribution system operator (DSO), Anell. The scenario incorporates the interconnection of two 20 kV DN feeders with a collocated 100 kW solar PV plant. The Residential Building Scenario represents: a small solar PV array, a battery ESS, an EV charger, and a connection to the local LV AC DN. The solar PV, ESS, and EV charger specifications represent example residential products [109,110] and the AC DN port is sized to accommodate these energy devices. A second building scenario depicts the offices, laboratories, and other work spaces of a facility building at the University of Strathclyde. This Scenario includes 6 ports: an 85 kW solar PV array, a 400 kW uninterruptible power supply (UPS) ESS, a 600 kW AC diesel generator, and critical AC and DC loads, all of which are connected to the 400 V AC DN. Finally, the Remote Community Scenario is defined according to the Dedza microgrid, which was designed by the University of Strathclyde and deployed in Malawi in 2020 [111]. The microgrid supports around 60 households using a 12 kW solar PVarray and an 8 kW 19.2 kWh battery ESS that interfaces to the local low voltage network where consumers can access the energy. Additional connection to the expanding medium voltage DN is forecast in the form of a potential future AC port.

4.2. Desirable feature weighting

4.2.1. Maximum voltage gain between ports

Voltage gain (which is defined here as the maximum voltage difference across a MPC's ports) is important to support the step-up of different voltage level devices [22]. This feature is beneficial for all of the scenarios described in Section 4.1, however, voltage gain becomes increasingly important as the scale of the step-up increases. Therefore, voltage gain is assigned a weight of: 1 for S2 and S3, which only interface LV devices, 2 for S4, which may be required to step its original port voltages up to MV levels during grid expansion, and 3 for S1, which will require the matching of LV RESs to the MV feeders.

4.2.2. Galvanic isolation

Galvanic isolation is assigned a weight of zero for the scoring of S3, due to its inclusion as a critical qualifying requirement for this application. Despite not being defined as a critical qualifying requirement for the remaining scenarios, isolation can be beneficial for these applications by offering an electrical disconnection between different ports and their voltages. Therefore, isolation is assigned an increasing weight with the need to interface higher voltage and current levels.

4.2.3. Voltage decoupling

Voltage decoupling is important to ensure that variations in any given port's output do not affect another port's operation. This decoupling is important when a MPC interfaces a variable output RES with other devices whose lifetime can be degraded by voltage and current fluctuations e.g. an ESS [112]. Although S1 does not interface a RES with an ESS, voltage decoupling is still deemed to be important due to the application's requirement for a fixed coupling voltage to maintain stable power transfer between the AC feeders [5]. Therefore, voltage decoupling is assigned a weight of 2 for all of the scenarios.

4.2.4. Resonance

Conventionally hard-switched converters can experience overlapping non-zero voltage and current values during their switch-on and -off that drives power losses and large EMI, particularly at high switching frequencies [113]. The hard-switching operation can also drive current fluctuations that impact the lifetime of ESSs [21,112]. Resonant circuits can be used to achieve soft-switching operation, which reduces the losses, ripple, and EMI and enables converters to operate at higher switching frequencies. A by-product of the potentially higher switching frequency is the ability to use smaller filter passive devices. Resonance is assigned a low weight of 1 for all applications as it is thought to offer improved efficiency for MPCs (which may contain many switches) [26] but can also be associated with complex control circuits and higher device stress [113].

4.2.5. Modularity

Modularity is defined here as the ability of a MPC to change its number of ports as its needs vary with increased ease and reduced cost compared to non-modular devices [19]. Modularity is assigned a weight of 3 for S4, which expects the number of ports to vary during either the MV grid expansion or the development of the remote community's needs. Modularity is assigned a weight of 1 for the remaining scenarios.

4.2.6. Scalability

Scalability indicates the ability of a topology to be extended to higher voltage/current levels by the arrangement of devices, submodules, or branches [114]. This feature stems from the different connection approaches of multilevel converters. Scalability is assigned a weight of: 2 for the likely higher voltage and power S1 application, 1 for S4, which may be extended to higher voltage levels in the future, and a weight of 0 for the low voltage Scenarios 2 and 3.

4.2.7. Number of switches, passive devices, and transformers

The number of switches, passive devices, and transformers all represent proxies for the cost, efficiency, and size of a converter. It is desirable to achieve a lower number of these components to reduce the cost and losses and to increase the power density of a MPC [13,14]. Transformers are considered independently from passive devices due to their significantly different scale. All three features are important for the feasibility of a topology so are assigned a weight of 2 for all of the scenarios.

Some of the reviewed topologies, particularly those that are scalable, can exist as multilevel configurations, whose number of switches, passives, and sometimes transformers vary depending on the given arrangement. To make the comparison between topologies fair, the number of components for these topologies is calculated for a single-level configuration, but the expected increase in cost and footprint with scale is discussed throughout.

4.2.8. Technology maturity

The maturity of topology types in industrially relevant conditions (e.g. application, power flow modes, and power and voltage levels) is included in the scoring to convey the potential cost and reliability of MPC development for the DN applications. Maturity is assigned a weight of 2 for all of the scenarios to achieve a balance between favouring more mature topologies while still enabling the identification of suitable new approaches.

Few examples of the specific MPC configurations for each study case exist, so instead, this feature describes the highest example of maturity for each topology class. Classes are scored according to an adjusted form of the Technology Readiness Levels widely used to describe technology maturity [115]. Classes are assigned a score of: 0 if topology components and functionality have only been validated in laboratory environments, 0.5 if similar topologies have been tested in relevant industrial environments, and 1 if similar topologies are widely used in industry for DN applications.

5. Results

The following Section describes the results of the Pugh Matrix Tool's comparison of MPCs for the four application scenarios described in Section 4.1. Topology feature scores (which are detailed in Table 4) are derived using the information identified throughout the literature review and then multiplied with the weights allocated to the Scenarios in Section 4.2 to give a topology's overall suitability score.

5.1. Scenario 1 – enhanced soft open point

Fig. 12 depicts the suitability scores of the topologies that qualify for the ESOP S1. Topology results are arranged by isolation class, which is introduced in Section 3. Topology names that are marked with an asterisk only qualify for S1's requirements using additional inverters.

The bidirectional non-isolated MPC is the only reviewed DC non-isolated topology (C1) that has sufficient bidirectional capability to qualify for S1. The UPQC and modular half-bridge topologies (C2) qualify and receive middle scores due to their desirable functionality, such as voltage decoupling and scalability, and their high maturity. However, their scores are degraded by the lack of recorded voltage gain. The UPQC receives a score contribution for partial isolation due to the presence of the shunt transformer that isolates one of the AC ports, despite not being classed as partially isolated.

Isolated topologies (C3 and C4) perform well for S1 due to their suitability for higher voltage applications (e.g. isolation and scalability). Partially isolated topologies (C5 and C6) also perform well but their suitability scores are degraded slightly due to the non-global isolation of ports.

5.2. Scenario 2 – residential building

Fig. 13 depicts the suitability scores of the topologies that qualify for the Residential Building S2. Fewer topologies qualify due to the different port configuration (now composed of 1 AC and 3 DC ports). The topologies that do qualify include isolated (C3 and C4) and non-integrated partially-isolated (C5) configurations, which receive similar scores for voltage decoupling and modularity. As a result, the main difference in score stems from the resonance, recorded voltage gain, and component count for the given application. Despite receiving a low score due to

Table 4
Topology feature scores.

Topology			Number of Ports					MVG	VD	RESO	MOD	SCAL	Switches	Passives	TC	TM
Ref	Name	C	Total	BD	AC	DC	ISO									
[57]	Bi-directional non-isolated converter	1	3	3	0	3	0	0.1	1	0	0	0	9	3	0	0
[52]	Cascaded boost converter	1	3	1	0	3	0	0.1	0	0	0	0	7	7	0	0
[53]	Magnetically coupled DC MPC	1	3	1	0	3	0	0.3	1	0.5	0	0	10	14	2	0
[63]	Reconfigurable inverter	2	3	2	1	2	0	0.1	0	0	0	0	19	14	0	0
[60]	Boost derived hybrid converter	2	3	1	1	2	0	0.1	0.5	0	0	0	9	4	0	0
[71]	Multilevel UPQC	2	N	N	2	N-2	1	n/a	1	0	0.7	1	(N-2)*3 + 54	(N-2)+15	3	1
[99]	Modular half-bridge-based converter	2	N	N	2	N-2	0	n/a	1	0	0.7	1	(N-2)*3 + 24	(N-2)+37	0	1
[79]	Series resonant MAB	3	N	N	0	N	N	0.6	1	0.5	0.7	1	N*8	(N-2)*2 + 8	1	0.5
[100]	Modular MF-based converter	3	N	N	2	N-2	N	n/a	1	0.5	0.7	1	(N-2)*8 + 48	(N-2)*2 + 32	1	0.5
[86]	Modular MT MAB	4	N	N	0	N	N	0.6	1	1	1	1	N*8	N*4	N	0
[87]	CLL resonant MPC	4	N	N-1	0	N	N	0.2	1	0.5	1	1	N*4	(N-1)*4 + 1	N-1	0
[83]	Dual-transformer asymmetrical TAB	4	3	3	0	3	3	0.2	1	0	0	0	28	7	2	0
[82]	Dual-transformer symmetric TAB	4	N	N	0	N	N	n/a	1	0	1	1	N*8	N*2 + 1	N-1	0
[78]	Buck-boost isolated DC converter	5	3	1	0	3	1	0.2	1	0	0	0	11	10	3	0.5
[90]	Two-stage AC-DC-DC MPC	5	N	N	1	N-1	N-2	0.1	1	0	1	1	(N-2)*8 + 20	(N-2)*3 + 5	1	0.5
[91]	Cascaded two-stage PFC and PSFB	5	N	N	1	N-1	N-2	0.9	1	0	1	1	(N-2)*4 + 20	(N-2)*4 + 6	1	0.5
[92]	Two-stage T-type battery charger	5	3	2	1	2	0	1	1	0	0	1	40	17	2	0.5
[96]	Dual 3-phase active bridge	6	4	4	2	2	2	0.1	1	0	0	1	24	20	3	0
[97]	Two-switch isolated MPC	6	3	1	1	2	0	0.2	1	0.5	0	0	12	13	1	0

Feature labels are abbreviated as follows: Class (C), Bidirectional (BD), Isolated (ISO), Maximum Voltage Gain (MVG), Voltage Decoupling (VD), Resonance (RESO), Modularity (MOD), Scalability (SCAL), Transformer Cores (TC), Technology Maturity (TM). N refers to the total number of ports for the given application. Feature values are shown in their normalised value unless dependent on N.

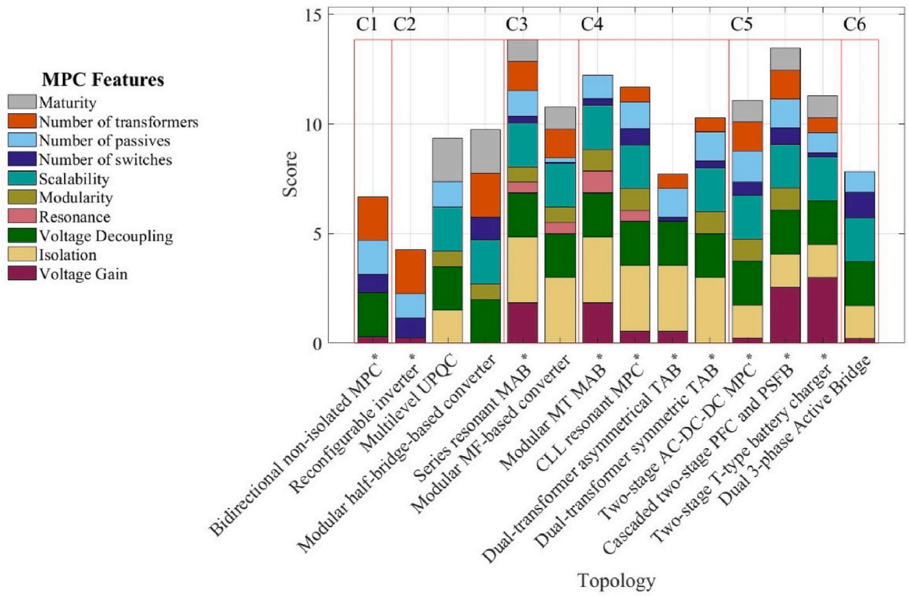

Fig. 12. MPC topology suitability scores for the ESOP application S1.

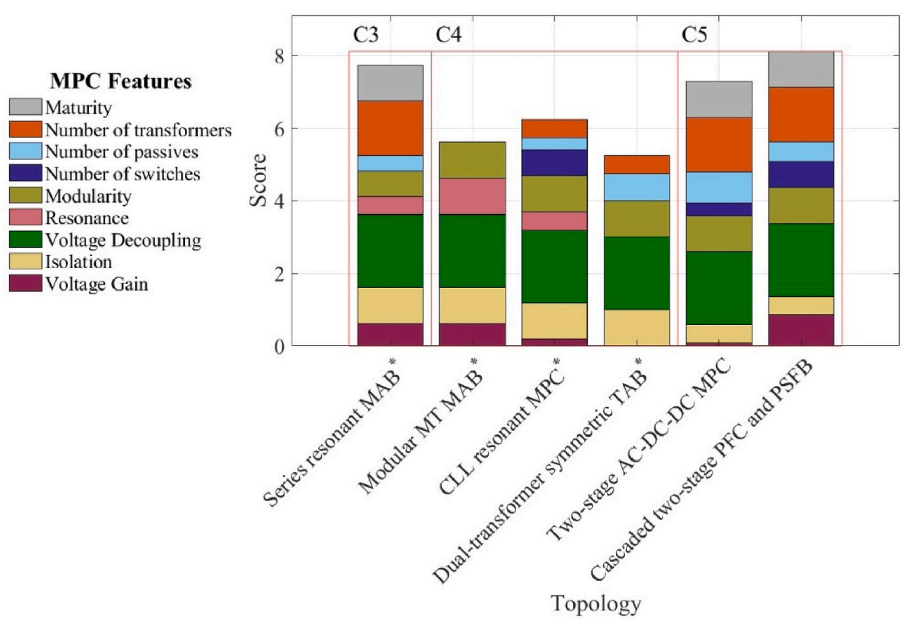

Fig. 13. MPC topology suitability scores for the Residential Building application S2.

their non-global isolation, partially isolated topologies achieve a good balance between the desired functionality and a low number of components.

5.3. Scenario 3 – facility building

Fig. 14 depicts the suitability scores of the topologies that qualify for the Facility Building S3. Topology names that are marked with a plus only qualify for S3's requirements using additional transformers.

A similar range of topologies qualify for S3 as S2, as well as some topologies that are more suited to support ACports e.g. the multilevel UPQC and the modular half-bridge-based converter.

The variation in score between the qualifying topologies stems from the recorded voltage gains, resonant ability, and component count. The topologies that best provide this functionality are the Series resonant MAB and the non-integrated partially-isolated MPCs (C5). The scores of the non-isolated (C2) topologies are degraded for this scenario due to the requirement for additional transformers to isolate the Protection Zone 0 ports from Zone 1+ ports but are boosted due to their technological maturity.

5.4. Scenario 4 – remote communities

Fig. 15 depicts the suitability scores of the topologies that qualify for the Remote Community S4. Most non-isolated topologies continue to struggle to qualify for this application due to their low bidirectional capability (or in the UPQC and modular half-bridge-based converter's cases, due to their unnecessary extra AC ports).

Qualifying topologies with modularity and scalability perform well, with the difference between several suitable topologies coming from the component count and voltage gain. The best performing topologies for S4 are the consistently highest scoring topologies for all of the

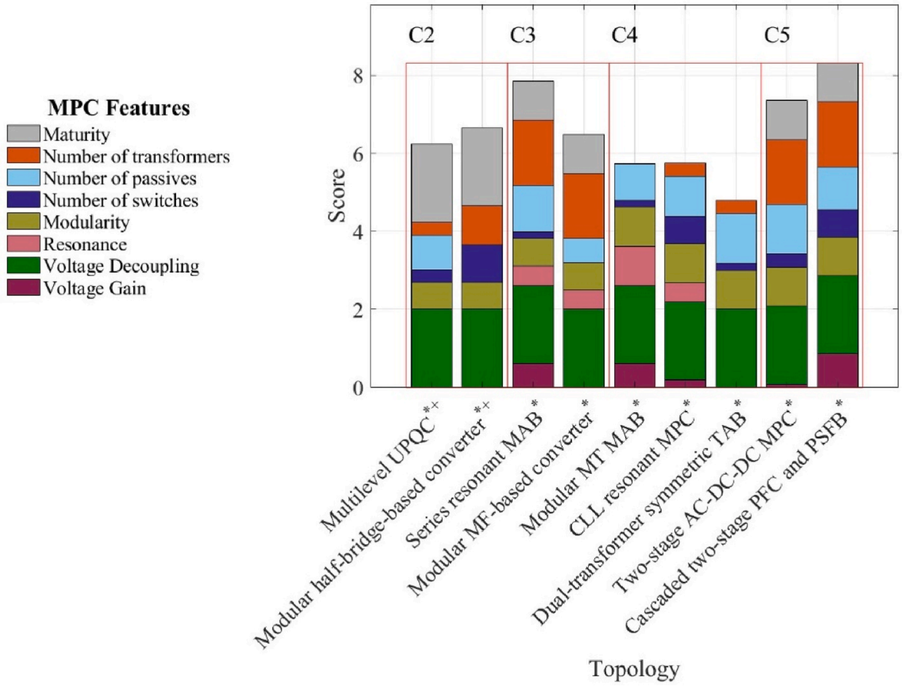

Fig. 14. MPC topology suitability scores for the Facility Building application S3.

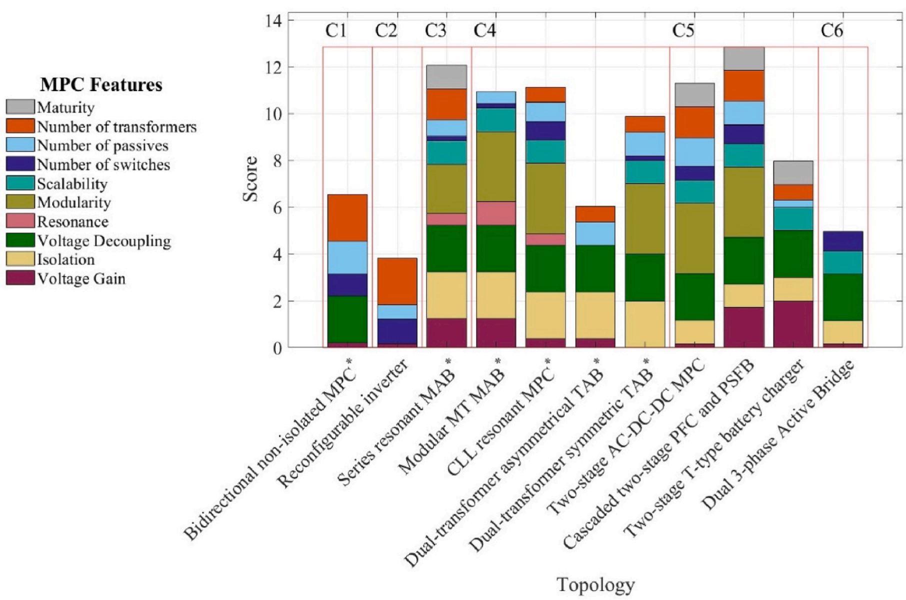

Fig. 15. MPC topology suitability scores for the Remote Community application S4.

applications: the series resonant MAB and the cascaded two-stage PFC and PSFB.

6. Discussion

The comparison tool enables the analysis of the suitability of a wide range of MPC topologies for the specific DN applications. The multilevel UPQC, which resembles a conventional multi-terminal converter configuration (other than the series transformer), could be suitable for the ESOP application due to its modularity, scalability, voltage decoupling, and the maturity of the conversion approach. The Pugh Matrix highlights that voltage gain is a key area for future research to verify the viability of the UPQC. The effective energy management of different ports should also be explored, which is an area of necessary research for many MPC topologies. However, the UPQC's results also signify the performance of conventional multi-terminal converter solutions, which require a large number of components to fulfil the given application's requirements.

Other non-isolated topologies did not perform well in the comparison due to their inability to be configured to the desired port specifications. When the bidirectional non-isolated converter did fit the scenario specifications, it offered a desirable component count but scored lower in other features. The results suggest that there is a gap for high efficiency, low component count non-isolated topologies to be developed with enhanced port and power flow capability. These topologies may extend the advanced two-port non-isolated configurations overviewed in Ref. [116]. Considering that the grid code and standard review suggested that isolation will be required between ports with highly different voltage and current ratings, the development of these DC non-isolated topologies should be focussed for low voltage applications.

Isolated and partially-isolated topologies performed well throughout the comparison due to their voltage decoupling, isolation, and scalability. However, each of the subclasses offered slightly different characteristics. For example, the multi-winding isolated family offered a low transformer count with high voltage suitability (enabling the series resonant MAB topology to perform well for the ESOP scenario) while the multi-transformer family offered high modularity (enabling the CLL resonant MPC to perform well for the Remote Community Scenario). Although the series resonant MAB was one of the highest scoring topologies for all of the applications it requires a large number of switches, which could be optimised in future work. The suitability of these isolated topologies should be assessed in more detail to understand their specific operational differences in normal and abnormal conditions, as well as the net benefit that resonance can offer considering the potentially increased complexity and additional components.

The cascaded two-stage PFC and PSFB (non-integrated partially isolated) topology consistently scored highly due to its balance of component count, modularity, and flexibility to be configured for the different applications. Additional analysis should be carried out to explore the efficiency of this topology, the device utilisation, and to prove its ability to integrate ports with different voltage levels. The significance of partial isolation (which degraded the score of this topology) should also be explored to identify if this feature is compromising for applications that do not require global isolation.

Additionally, future research might address the integration of isolating stages into the MPC. Transformers are conventionally integrated into MPCs as DC to DC conversion stages. The definition of case studies in this work highlights that isolation is commonly a requirement for AC ports, which drives the necessary addition of at least one inverter to interface an isolated DC port for all of the qualifying topologies in S3. Future research could explore the non-conventional integration of isolating stages into an MPC to optimise their correlation with AC ports, alongside the balance of size, efficiency, component count, and functionality.

In general, the top performing topologies in the comparison agree with the few examples of high maturity or market-ready MPC solutions that were identified in the literature review; some conventional multi-converter solutions are being pursued due to the extensive existing knowledge and ease of deployment [117,118] while multi-winding isolated and non-integrated partially isolated solutions are being pursued [80,81,93] due to their suitability for different voltage levels, scalability, modularity, and ability to meet application specifications.

One weakness of this comparison tool is its inability to account for detailed features of the MPC operation (such as the increasingly complex control as ports and cross couplings increase [19]) and the scaling for higher voltage levels (where all topologies were compared as single-level configurations). These details represent critical areas to develop MPCs for MV applications. Examples of future work include: the impact that different submodule cell building blocks have on MPC operation and the optimisation of multilevel MPC scales considering voltage level, efficiency, and cost (similar to Ref. [114]). Another issue is the use of subjective weights that could be varied for different applications and objectives, however, significant justification has been provided to allow the comparison to identify pathways to improve the maturity of MPCs.

As well as the analysis of converter operational features, it will be essential to assess the benefit that MPCs bring to the grid. The hypothesis presented at the beginning of this review suggests that MPCs offer: the better utilisation of low carbon energy due to the optimised management of energy ports with the effective support of local grid requirements, all at potentially higher efficiencies due to a lower number of conversion stages. MPCs should be assessed in terms of power quality, capacity for grid support, and the potential to introduce interactions on the network, with respect to other two-port and multi-terminal converter configurations.

7. Conclusion

This work presents an overview of key multiport power converter (MPC) topologies for a range of low and medium voltage distribution network applications. Initially, the technical and safety standards that existing converters are subject to are reviewed to identify the baseline capability that MPCs will need to possess. The review suggests that MPCs may need to galvanically isolate high voltage and current ports from lower rated ports. Representative MPC topologies from a wide range of families are then reviewed, with reference to their operational characteristics.

A Pugh Matrix comparison tool is developed, which allows the utilisation of the literature review data to identify suitable topologies for four DN applications as well as areas for future research. Many of the non-isolated topologies are found to lack sufficient flexibility to be made to fit the application scenarios, meaning their desirable high efficiency and low component counts cannot translate to high scores. This finding suggests that there may be a niche for the continued development of non-isolated MPC topologies that can support multiple power flow modes while still offering high efficiency and low size. Their lack of any isolation suggests they may be most suitable for low voltage applications. The mid-level performance of AC-DC non-isolated topologies suggests they could be pursued, particularly due to their modularity, scalability, and the experience that can be applied to these configurations from conventional multi-terminal solutions.

Isolated and partially-isolated topologies scored well due to their ability to support different port numbers and types. The different families offered different characteristics but the multi-winding isolated and non-integrated partially-isolated classes generally performed best due to the weighting that depended heavily on component count in this study. The comparison tool highlighted the proof of partially isolated topologies on medium voltages as a key area of future research.

The high-level comparison tool was not configured to account for control complexity, the cost and size of scalable multilevel configurations, and the dynamic characteristics and stability of the different topologies. All of these areas point to the additional work that needs to be carried out for MPCs to identify the optimal topologies for the given applications and to confirm their benefit over conventional multi-terminal two-port converter solutions for the cost-effective integration of devices into future decarbonised distribution networks.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sam Harrison, Bartosz Soltowski, Lie Xu, Agusti Egea-Alvarez reports financial support was provided by Innovate UK. Antonio Pepiciello, Andres Camilo Henao, Ahmed Y. Farag, Mebtu Beza, Marc Cheah-Mane, Oriol Gomis-Bellmunt reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This project was funded by the Innovate UK Horizon Europe Guarantee application number 10039599. This work was also funded by the

European Union's Horizon Europe research and innovation programme in the framework of the project "iPLUG" with grant agreement 101069770.

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