iPLUG

Deliverable D1.1

Overall requirements, specifications, KPI, and use case definitions

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1 Executive summary

This report, Deliverable 1.1 of the iPLUG project, overviews the work that has been carried out as a foundation to stimulate the design of Multiport Power Converters (MPCs). The report details the grid requirements and KPI selection, as well as the definition of the topology, architecture and use cases.

Multiport Power Converters (MPCs) are defined as any device that interfaces more than two energy ports. A classification structure is then developed that allows all MPCs to be categorised, and therefore compared systematically, in terms of isolation type.

Three distinct scenario groups are identified where MPCs can provide significant benefit. These scenarios are: 1) distribution network support, 2) building connections (including residential and facility buildings), and 3) remote communities. Specific cases and data sources are identified, which will allow later iPLUG research to be tailored for particularly valuable applications.

The grid code and safety standard requirements for low- and medium-voltage converters and converter-interfaced devices are reviewed to identify the base requirements that MPCs are likely to be asked to comply with. The review shows that the requirements expected of conventional converter devices on these voltage levels are becoming more strenuous and advanced control requirements to support the local grid are beginning to be defined in grid codes. Galvanic isolation is not found to be required of converters on low- and medium-voltages but is described as offering significant benefits for the safe operation and interconnection of different voltage levels. The structure of future MPC requirements is also discussed, highlighting the complexity of imposing conventional specific energy source requirements on a device that will interface multiple different energy sources.

A set of key performance indicators (KPIs) are developed that describe the benefit that MPCs can offer and allow the comparison between different topologies. The KPIs are separated into network and converter KPIs, where the former describes the benefit that MPCs can bring to the grid and the latter describes the beneficial characteristics that MPCs can offer in comparison with conventional converter solutions.

A review of existing MPC configurations is carried out to identify the characteristics of different topologies and the gaps in the field where iPLUG research should be pursued. The review establishes a set of key features (which can be gathered from the literature review without needing additional studies, different to the KPIs) to describe topology characteristics. A Pugh Matrix scoring method is used to identify the topologies and features that are suitable for the iPLUG applications. The scoring highlights that several partially-isolated configurations are particularly suited to the iPLUG scenarios. The scoring method and review also highlight that further effort needs to be made to optimise the sizing of devices for a given voltage level and to explore the nuance of MPC control operation.

Finally, the features and considerations of control and communications for MPCs are outlined. From this overview, MPC operation is deemed to be feasible using DSP or FPGA devices, both of which are shown to be able to support the expected complex power converter operations.

2 Introduction

The decarbonisation of the energy industry is associated with a large increase in the number of power converters. Multiport power converters (MPCs) are power converters that control the exchange of power between more than two ports. They have generally been developed to increase the efficiency and power density of applications that are associated with numerous conversion stages [1]–[3]. The iPLUG consortium aims to develop innovative designs and controls to advance the field of MPCs to support the effective transition to net-zero. This report is the first deliverable of the iPLUG project (D1.1) and offers an introduction to the definition of MPCs, the benefit that they can provide to certain applications, and the fundamental requirements that they will need to meet to connect to the grid. Reviews of existing MPC topology and control solutions are carried out to overview the existing state of the field and to guide iPLUG's further work.

An explicit definition of MPCs is offered in Section 2.1, which includes a categorisation structure that can be used to consider and analyse the MPC literature more easily. The specific applications that MPCs have been identified to offer benefit to are introduced and described in Section 3. This section will also detail the sources of data and their resolution that are available for later stages of the iPLUG analysis.

MPCs will have to meet standardised specifications to connect to the grid. It is expected that these may be developed from the existing requirements that are asked of conventional power converters on low and medium-voltage grids. Some additional requirements may also be expected. The existing requirements are reviewed and detailed in Section 4, alongside some further discussion on the possible formation of MPC requirements.

Many proposed MPC topologies have the potential to meet these base requirements e.g. [4]–[6]. However, the purpose of the iPLUG project is to maximise the cost-effective performance of MPCs, both in terms of their own operational efficiency and the benefit they can bring to the transforming electric grid. Therefore, the Key Performance Indicators (KPIs) that will be used to quantify the capability of different MPC topologies are introduced in Section 5. These are organised as either network KPIs, which describe the ability of MPCs to support the grid, or as converter KPIs, which describe the operational characteristics of the MPC itself.

High-level key features (which are mostly distinct from the KPIs) are also introduced and used in Section 6 to offer an initial overview of the MPC field. These key features are detailed alongside a Pugh Matrix Weighting and Scoring Method [7] to allow the systematic identification of the varying importance of topology characteristics for different applications (derived from those identified in Section 3). A review of existing MPC topologies is then carried out in Section 6.3 in terms of these features. The Weighting and Scoring Method is applied and analysed in Section 6.4 to assess suitable topologies, the reason for their suitability, and to identify areas for further iPLUG research.

Finally, none of the reviewed topologies could be implemented without the appropriate control and communications devices. Section 7 reviews the existing communications approaches and standards that are employed/required to achieve similar converter operations as MPCs. Then, the control boards available to implement MPC operation are compared. The overarching conclusions and corresponding future direction from this initial report are then provided in Section 8.

2.1 Definition of multiport power converters

The core feature of all multiport power converters investigated by the iPLUG consortium is their capability to integrate various power appliances, generation systems, distribution lines, and loads making use of techniques providing control of more than 2 ports. As such, complexity of MPC control is higher than in cases of simple power converters with typically one input and one output section of the device. The iPLUG consortium is focussed on the development of MPCs for low and medium voltages, ranging from several volts to less than one hundred kilovolts.

The fundamental outcomes expected from future research activities aim to highlight crucial benefits resulting from the integration of wide range of devices using MPC over conventional methods to achieve similar functionality. Anticipated benefits could show advantages resulting from use of MPC considering power conversion efficiency, cost or footprint. Details highlighting the proposed assessment for comparison are presented in Section 5 of this document summarising Key Performance Indicators (KPIs).

Some MPCs are based on topologies providing a single power conversion stage. This group of converters is divided between two categories - isolated and non-isolated MPCs, depending on method used to transfer power between devices connected to individual ports of the MPC. Isolated converters make use of a power transformer providing galvanic isolation using high frequency modulation techniques. The isolated family is composed of two classes of topology: C1 – multi-winding single transformer and C2 – single winding multi-transformer. Non-isolated converters maintain direct physical connection between all ports integrated under the scheme. The non-isolated family is further classified as either: C3 – DC capable or C4 AC and DC capable topologies.

The third group introduced within the MPCs classification involves hybrid multistage MPCs. Such MPCs are designed based on two or more power conversion stages and typically contain isolated and non-isolated sections. This partially isolated family is further classified as either: C5 – non-integrated or C6 – integrated topologies. The summary of the proposed classification is presented in Figure 1.

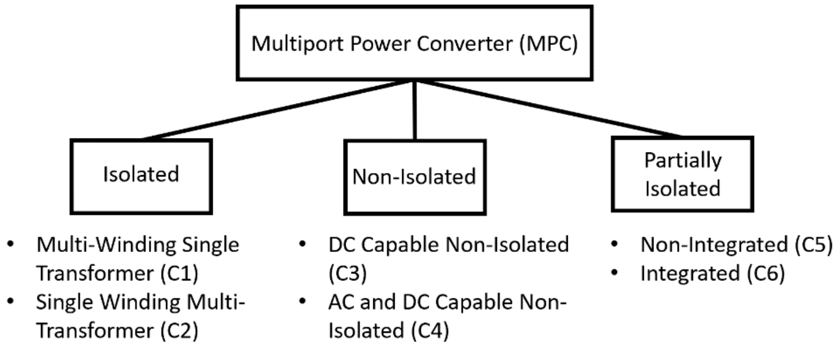


Figure 1 Multiport Converter Classification

3 Study Cases

3.1 Introduction to Study Cases

This section of the reports provides a summary of selected case studies where iPLUG Multiport Power Converter (MPC) could be implemented. Each scenario indicates a specific application where a minimum of three ports are used. Provided examples have been categorized into three groups – each representing different application of the MPC. The first group highlights potential applications in the power system where iPLUG solution could enhance power management and voltage stability of either MV or LV distribution networks. The second group of scenarios involves community interconnections where microgrids could deliver renewable electricity either locally or using external connections with neighbouring systems or with the power grid. The third group involves household installations where MPC could improve power conversion efficiency and reduce the integration cost of batteries, solar panels and some appliances.

3.2 Distribution Networks Support

The first group of study cases presents scenarios where MPC interconnects two or more networks in order to accommodate better power management between them. Given case studies indicate MV as well as LV distribution networks with potential for adoption of distributed renewable energy capacity.

3.2.1 Coupling MV Networks at different Voltage Levels

Scenario 1:

The first scenario for SOP under MV networks is proposed by Estabanell (Distribution System Operator in Spain) [8]. The case study investigates introduction of MPC to integrate two MV feeders operating at 20 kV and 5 kV. As such, better voltage management and power distribution could be obtained in given scenario.

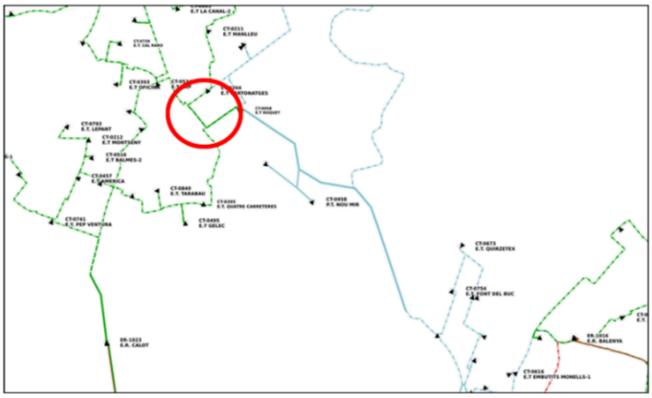


Figure 2 Multiport Converter for MV Networks – Scenario 1

Furthermore, the example is also intended to provide additional port to host 100 kW of solar generation. Appropriate power management using proposed converter would therefore govern power flows between each MV network to maximise efficiency of the system which could result in better utilisation of renewable electricity. Network topology used to illustrate such scenario is presented in Figure 2.

The summary highlighting MPC configuration, number of connections and types of feeders/appliances connected to each port is highlighted in Figure 3.

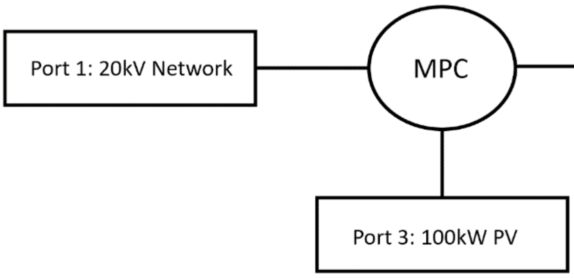


Figure 3 Multiport Converter for MV Networks – Configuration

Scenario 2:

Second scenario in Section 3.2.1 also involves interconnection between two MV networks – 20 kV and 5 kV. Scenario 2 introduces additional challenges with balancing of power between feeders due to existing connection of renewable generation at 5kV network feeder. After introduction of MPC, solar generation curtailment could be minimised to maximise overall renewable generation utilisation factor and to improve stability of the network. Third port of the MPC is expected to host further distributed generation resources at given location.

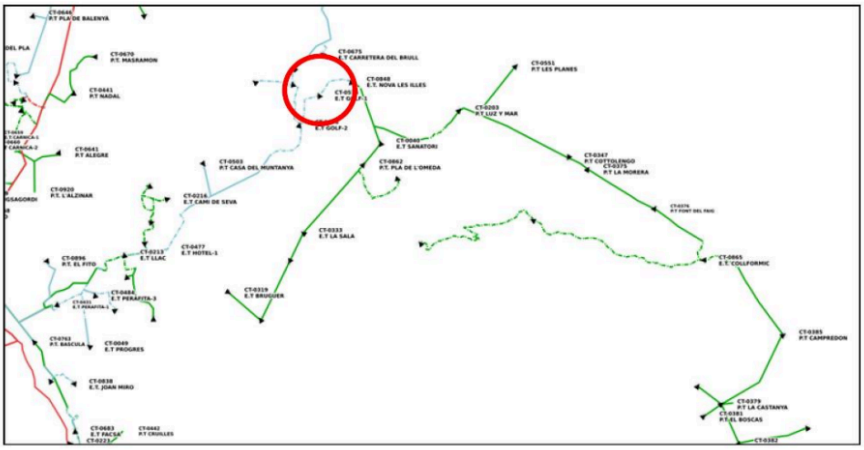


Figure 4 Multiport Converter for MV Networks – Scenario 2

3.2.2 Interconnection between multiple LV lines at different voltage levels

The following scenario considers interconnection of three LV lines – two operating at 400 V and one at 230 V. Furthermore, given network has the potential for installation of up to 100 kW solar generation. Smart management between LV lines gives capabilities to improve renewable utilisation by sharing power between individual lines in a given system. Network topology for this scenario is presented in Figure 5 below.

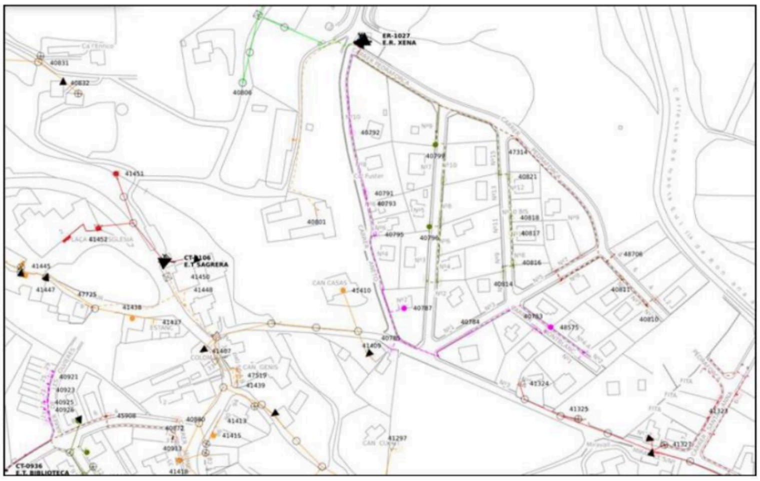


Figure 5 Topology of a Network for Interconnections between Multiple LV Lines at Different Voltages

The summary indicating MPC arrangement under this scenario is presented below where MPC has four input ports – three for networks interconnections and one for installation of renewable electricity generation.

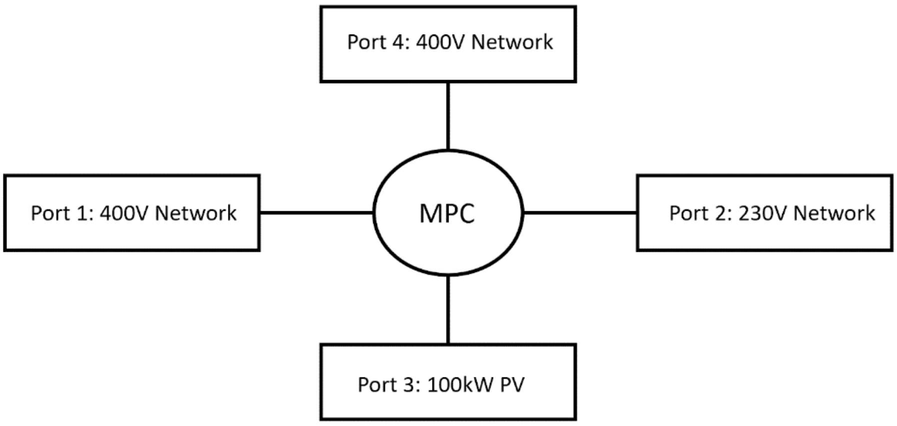


Figure 6 iPLUG Multiport System Configuration for Interconnection between Multiple LV Lines at Different Voltages

3.2.3 Coupling of MV Lines at the same Voltage Levels

Scenario 1:

Another example proposed by Estabanell considers use of MPC for interconnection of two MV lines operating at the same voltage level. A potential third port would also involve integration of solar generation with the remaining part of the grid infrastructure. Similarly to case scenarios presented under Section 3.2.1, interconnection between two lines provides capabilities to improve power flows between feeders simultaneously enhancing networks voltage management. Such arrangement would also maximise hosting capacity for renewable energy systems.

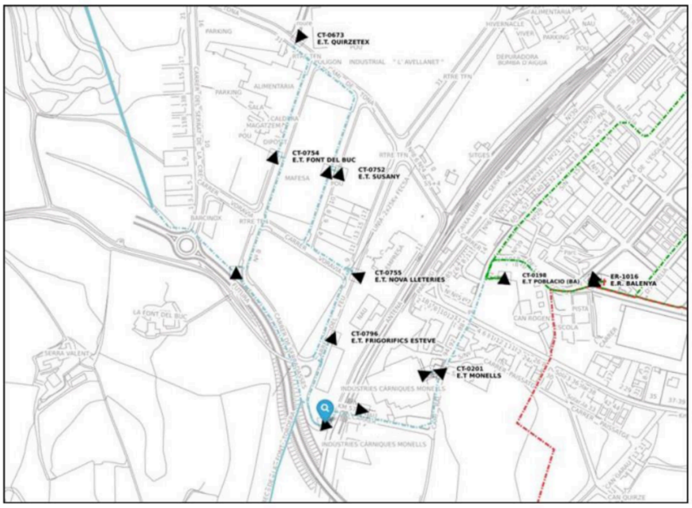


Figure 7 Topology of a Network Coupling MV Lines at the same Voltage Levels – Scenario 1

The summary of the iPLUG multiport design for Scenario 1, case 3.2.1 is illustrated in Figure 7 below.

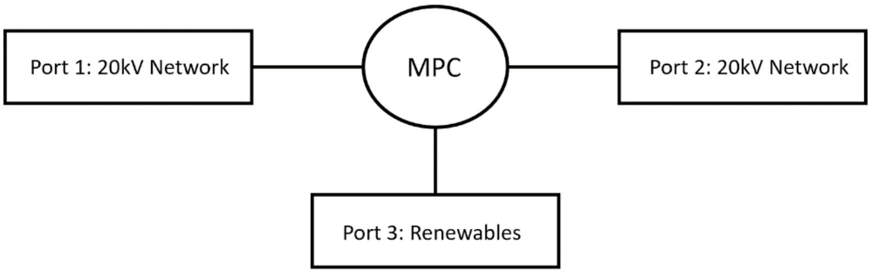


Figure 8 Interconnection of MV lines and Integration of Renewable Capacity

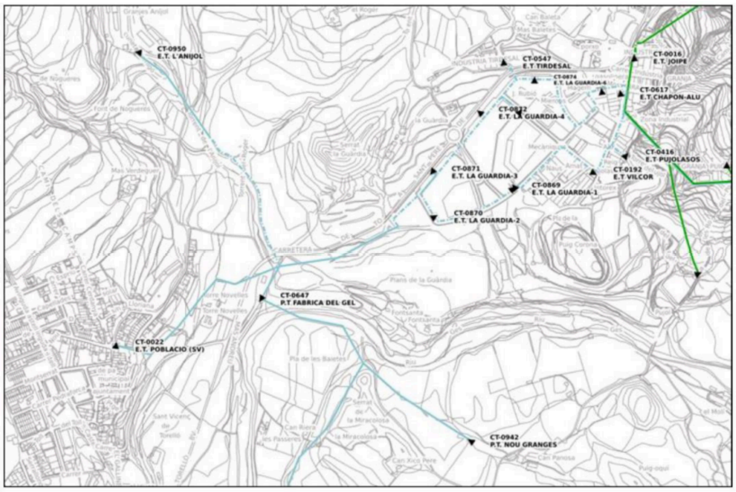


Figure 9 Topology of a Network Coupling MV Lines at the same Voltage Levels – Scenario 2

Scenario 2:

Scenario 2 introduces the same topology of the iPLUG MPC as presented in Figure 8. This time the system involves a scenario of the MV system in rural areas. The network topology is presented in Figure 9.

3.2.4 Low Voltage (LV) Networks in Residential Areas

Group of scenarios presented in Section 3.2.4 involves introduction of multiport converter in residential areas with future connection of electric vehicles (EVs) and distributed renewable generation. Given example has capability to interconnect two LV lines available in the region to improve balance of loads, voltages, and renewable capacity. Topology of given system is presented in Figure 10 below.

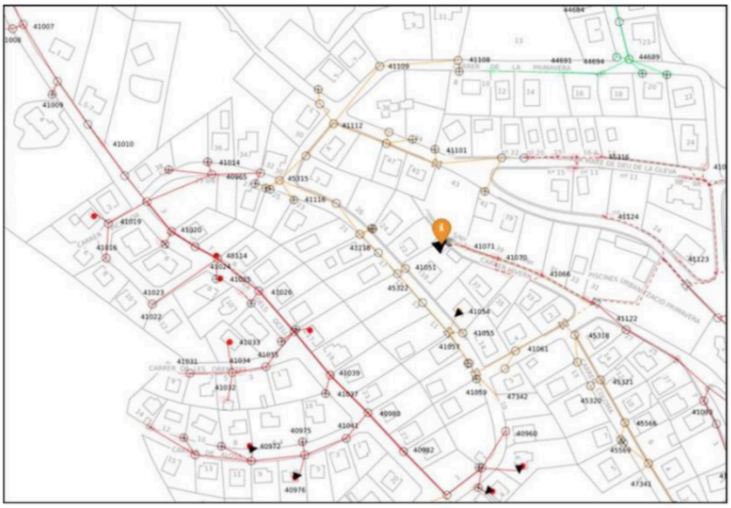


Figure 10 Multiport Power Converter for LV Residential Area Topology

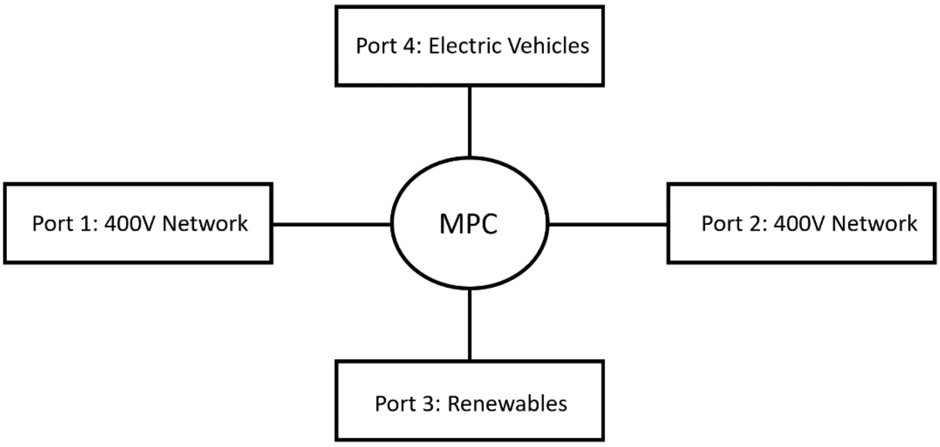


Figure 11 iPLUG Converter for LV Residential Areas

Configuration of the proposed iPLUG converter for a case 3.2.4 is presented in Figure 11.

3.2.5 Medium Voltage Grid

Another example considers installation of MPC within medium voltage 40 kV system. This involves interconnection of two lines at 40 kV with additional port for introduction of distributed energy resources. This case study would investigate the maximum power capacity installed under such configuration in order to maintain safe operation of the system.

40 kV Grid presenting medium voltage configuration for MPC is presented in Figure 12.

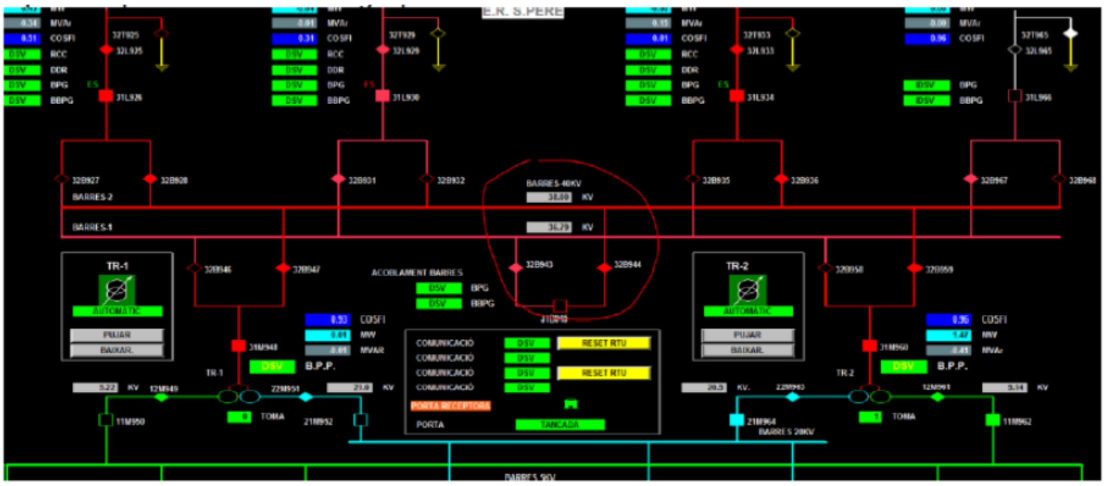


Figure 12 Medium Voltage Grid for iPLUG MPC

The configuration of the MPC system revealed in Scenario 3.2.5 is presented in Figure 13.

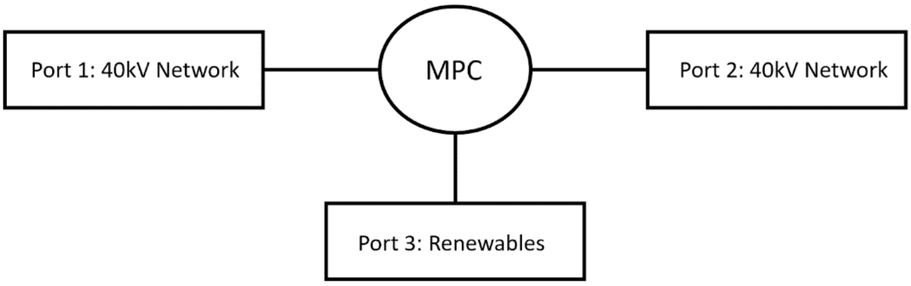


Figure 13 MPC for a Medium Voltage Level

3.3 Interconnected Communities

Section 3.2 of the document primarily focuses on identifying applications for iPLUG MPC within power distribution systems. Section 3.3 provides different application for the MPC, in regions where iPLUG could improve system resiliency by interconnecting communities. Such solution might be applied in areas where a group of electricity consumers relies on local generation and storage to meet their energy demand. Furthermore, additional ports of MPC could be utilised to connect neighbouring communities with similar system topologies. As a result, electricity exchange could be obtained between microgrids to maximise system reliability and renewables utilisation factor. Other ports could be used to connect with the main power network either to import electricity from the grid or export surplus of renewable power. Proposed system introduces high resiliency and could be used in regions where power outages frequently occur. As a result, interconnected community networks could always maintain security of power supply for the critical electric demand.

MPC for interconnected communities finds its applications in rural locations such as Scottish Highlands where isolated renewable energy system deliver electricity for local communities using hydro power, wind and solar [9]. Other applications of such systems occur in Sub-Saharan Africa where solar off-grid electricity is prevalent and specification of technologies for future interconnection between solar microgrids and power system are yet unknown [10] Another case where interconnected community networks could show its application is within “conflict zones”. As such, with a support of novel iPLUG MPC frequent power outages forced on transmission and distribution system would not affect electricity delivery within communities supported by local microgrids.

For the case study representing Interconnected Communities, microgrid system installed by the University of Strathclyde is proposed. Such network is deployed in Dedza district in Malawi [11]. The system is supplied by 12 kW PV and delivers electricity to approximately 60 low-income households. University of Strathclyde has access to full remote monitoring system. Measured data cover period between 2021 and 2023 and involve monitoring of aggregated power consumption within the microgrid, state of charge of the battery and power used to charge the system using solar electricity.

Figure 14 Dedza Microgrid in Malawi

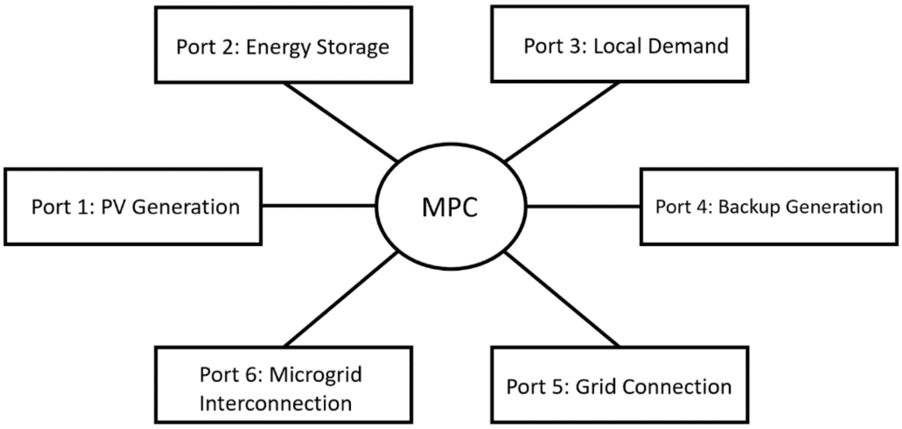


Figure 15 iPLUG for Resilient Interconnected Communities

Interconnecting communities could be provided by developing appropriate interaction between up to six ports. The proposal for such architecture is summarised in Figure 15.

3.4 Building Connections

3.4.1 Smart Home Installation

Section 3.4 introduces household scenario for use of MPC. In given studies, MPC could be used to interconnect local renewable energy systems with the distribution grid. Furthermore, several ports of the converter can be developed to support local energy storage system and electric vehicles. Introduction of MPC within household installation can bring significant benefits such as improved system efficiency and reduced renewable, EV and energy storage integration costs in comparison to conventional methods. Example presenting proposed scenario is provided in Figure 16.

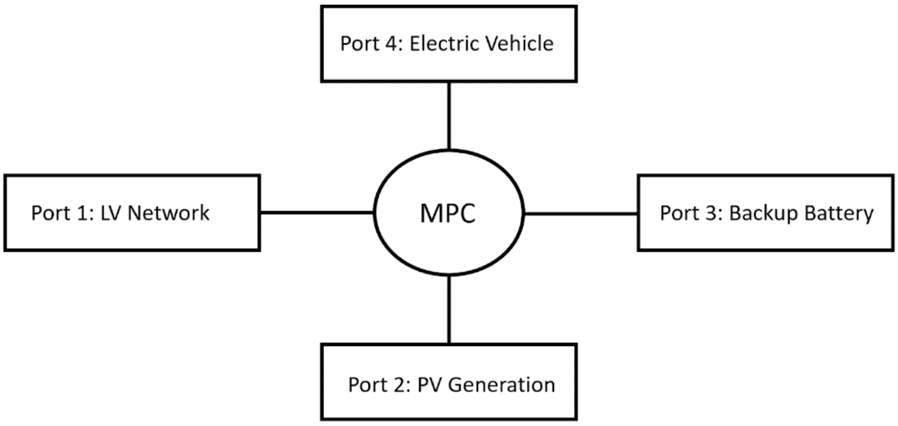


Figure 16 iPLUG for Domestic Households

3.4.2 MPC for Facility Buildings

Figure 17 MPC for Interconnection between Buildings

Another scenario for building installations has been proposed by Infraestructures [12]. This case study considers interconnection of five public buildings that are currently equipped with solar generation. Locations of each building for this specific scenario are presented in Figure 17**.**

Adoption of MPC for Scenario 3.4.2 gives chance to improve power management of distributed energy sources. It also provides opportunity to adapt DC network architecture for rapid charging of electric vehicles. Given configuration is also expected to provide bidirectional electricity exchange with the main distribution network using EVs and local battery systems.

Interaction between all technologies listed in this scenario using MPC should also allow “system islanding” to operate as independently from the main network while experiencing faults on the main distribution system.

3.4.3 Technology and Innovation Centre (TIC) and Strathclyde Gardens

Case study 3.4.3 has been proposed by the researchers from the University of Strathclyde. MPC ports under this scenario integrate 85 kW solar array as well as 400 kWh battery energy storage providing electricity to critical loads while the main electricity supply is not available. The critical loads could also be supported by a backup diesel generator after batteries run out of capacity. All devices in TIC are monitored and access to data measured between 2015 and 2023 can be granted.

Additional ports in case study 3.4.3 aim to provide connection with AC LV network and DC appliances. DC section is known as being part of the "Strathclyde Gardens" concept proposed by the UoS in 2019. Its purpose is to utilise new DC distribution infrastructure to supply a wide range of appliances around gardens at the UoS. All DC appliances considered are divided between two subgroups, as presented below.

High Power DC (HPDC):

- EV Charging stations (50 kW CHAdeMO)
- Solar PV Systems (50 kW)
- Battery Energy Storage System (2x30 kWh)

Low Power DC (LPDC):

- Smart DC Lighting
- CCTV Camera
- Outdoor Solar Benches and Workstations
- Wifi Routers
- Interactive Information Screens

As a result, the proposed configuration for TIC integrating DC Gardens would involve a minimum of 6 ports:

- Port 1 – LV network
- Port 2 – Battery Energy Storage System
- Port 3 – PV Array
- Port 4 – Diesel Generator

- Port 5 – DC Garden Loads
- Port 6 – AC Critical Loads

3.4.4 Primary School Lledoner – Granollers

This case study introduces an LV scenario where MPC could integrate local PV generation of 22 kW with other appliances including electric vehicle charging points and battery energy storage. To date, Lledoner – Grenollers primary school has been powered by a local PV array. EV charging infrastructure and batteries have not been put in place yet. The total contracted capacity for this scenario is 55 kW with option to upgrade the PV array from 22 kW to approximately 100 kW.

Further studies to be conducted require investigation for optimal configuration of the MPC integrating all listed devices. MPC should be able to maintain optimal voltage stability. It is expected to provide power supply while being disconnected from the main distribution network.

Based on given description, given scenario should provide a MPC with 4 ports integrating

- PV Array
- EV charging point
- Battery Energy Storage System
- Local LV Network

Types of measurements and data available to support this case study are listed below.

- Smart Meters data (Load and PV production), with resolution 15 min
- Smart Meters Historics, 1 hour resolution
- Grid Topology (QGis) and LV network data
- SCADA Data Historics, with 1 hour resolution

3.4.5 Tona High School

This scenario presents a similar case study 3.4.4. Tona High School is currently equipped with 22 kW of solar generation. Furthermore, two additional other solar arrays could be provided, each supporting 111 kW and 178 kW of power. The project also considers the future installation of electric vehicle charging points (3 ports dedicated so far) as well as battery energy storage system. As a result, the overall design of the MPC would involve integration of 6 ports, as presented below:

Port 1: Existing 22 kW PV array

Port 2: 111 kW PV Array

Port 3: 178 kW PV Array

Port 4: Electric Vehicle Charging Points

Port 5: Battery Energy Storage System

Port 6: LV Network

Similarly to case 3.4.4, MPC within Tona High School is required to maintain safe operation of the local network, operate as islanded microgrid as well as stabilise internal voltages at each port.

Data available supporting case studies is listed below:

- Smart Meters data (Load and PV production), with resolution of 15 minutes
- Smart Meters Historics with 1 hour resolution
- Grid Topology (QGis) and LV network data
- SCADA Data Historics, with 1 hour resolution

3.4.6 Courts of Granollers

The final scenario considers integration of a solar PV array using MPC where 4 ports are required. Courts of Granollers system is not equipped with any solar generation at the moment - first installation of 40 kW is expected next year. Contracted power in the facility is 300 kW. The case study proposes installation of three EV charging stations as well as battery energy storage system.

Similarly, to cases 3.4.4 and 3.4.5, Courts of Granollers scenario requires optimisation of power flows to maintain appropriate voltage stability. The system should also have capabilities to self-balance local electricity supply and demand in cases when LV network is not available. Data available for case study 3.4.6 is listed below:

- Smart Meters Historics, with 1 hour resolution
- Grid Topology (QGis) and LV network data
- SCADA Data Historics, with 1 hour resolution

3.5 Overview of iPLUG Scenarios

Sections 3.2 - 3.4 introduce a wide range of scenarios proposed for use of MPC. High level summary of all study cases supporting further steps of investigation is presented in Table 1.

Table 1 Summary of iPLUG Study Cases

Application Type	Scenario	Number of Ports	Data Availability	Comments	Project Ownership
Networks	MV Networks at different Voltage Levels	3	Full	Network monitoring available	Estabanell
Networks	Multiple LV Lines at different Voltage Levels	4	Full	Network monitoring available	Estabanell
Networks	MV Lines at the same Voltage Level	3	Full	Network monitoring available	Estabanell
Networks	LV Networks in Residential Areas	4	Full	Network monitoring available	Estabanell
Networks	Medium Voltage Grids	3	Full	Network monitoring available	Estabanell
Building Connections	Smart Home Applications	4	Partially Available	Demand profiles not available	CUT
Building Connections	MPC for Facility Building	5	Requires some assumptions	Some appliances not installed yet	Infrastructureas
Building Connections	Technology and Innovation Centre and DC Gardens	6	All data available	All data available	UoS
Interconnected Communities	Dedza Microgrid	6	All data available	All data available	UoS

3.6 Case Studies – Conclusion

Section 3 of the report gives a summary of 13 study cases proposed for further assessment of MPC feasibility. Each of listed scenarios was proposed by one of the iPLUG consortium partners capable to provide additional data supporting further studies.

Out of all study cases, several with the highest priority and data availability will be selected for further investigation. It is anticipated that at least one scenario for LV and MV networks will be chosen as well as one case study presenting building applications.

Appropriate definition of study cases for MPC gives a solid understanding of range of standards and regulations required to follow while implementing MPC with the existing electrical infrastructure. This is summarised in Chapter 4 of this document.

4 Grid codes and requirements

4.1 Introduction

This section is composed to fulfil Tasks 1.1.1:2 of the iPLUG project by overviewing the Grid Code (GC) and industrial standard requirements for devices connecting to low- and medium-voltage networks. The objective is to present a representative overview of the features and operational ranges expected from any device that might be incorporated in a multiport converter at these voltage levels. The findings will be used to inform the design and development of the multiport converter.

The assessment is split into two sections. A review of technical capabilities is built from recent review documents of relevant GCs (detailed in Section 4.2) to save time (and avoid repetition), while specific GC and grid-integration standard documents are also assessed individually where necessary. The findings are summarized in Section 4.3, which introduces and gives examples of the critical requirements.

A review of the safety standard requirements for converters interfacing different energy sources (that may be interfaced by MPCs) is then carried out in Section 4.5, where the relevant safety standards are introduced in Section 4.4.

Section 4.6 then discusses how all of the identified requirements should inform multiport converter (MPC) design/integration.

4.2 Relevant grid code reviews

The literature that reviews relevant GCs is identified and detailed in Table 2. The documents provide an overview of the GC requirements for devices that are likely to be incorporated in the LV or MV MPCs (according to the Study Cases identified for Task 1.2.5) or that have similar operational features as the planned MPC (e.g. HVDC).

Reference [15] serves as a basis for the study as it provides a thorough and recent analysis of distributed energy resource (DER) connection requirements, which is relevant for the devices likely to be interfaced by MPCs. As well as [15], specific data are compiled in the following sections from [17], which provides a useful overview of requirements for devices connected to low voltages, and from [19], which provides the most recent assessment of LV and MV connection requirements. Data is also compiled from recent grid-codes that had not been covered in any of the reviews, specifically from the Great British System Operator’s (SO’s) update to account for grid-forming (GFM) control [25] and the recent update of the IEEE standard 1547 to consider the capability and requirements of energy storage systems (ESSs)[9]. Additional data describing fast-frequency services that are not included within GCs are also compiled and the sources are detailed in Table 8.

The review identifies that significant discussion is made for the requirements for distributed generators on LV & MV networks due to the additional issues they pose for the network. However, the MPC design is also likely to interface devices that consume energy and is therefore also interested in their requirements. An additional subsection is included that discusses the specific requirements for these devices. For example, MPCs are being considered to provide a similar function as interconnectors between isolated radial systems. The proposed requirements for MVDC [21] and the existing requirements for HVDC [27] interconnectors are considered. Although not explicitly applicable to the relevant LV or MV conditions, these latter HV requirements are included due to the increased industrial experience compared to their MV counterpart's. The requirements for loads on the GB DN are assessed [28] as well as existing and proposed requirements for electric vehicles (EVs) [23], [24].

Table 2 Reviews of grid codes to be considered throughout Tasks 1.1.1:2.

Reference	Technology/ application	Date	Title	Author
[13]	Grid-connected RESs	2020	Grid-connected renewable energy sources: Review of the recent integration requirements and control methods	Al-Shetwi et al.
[14]	Grid-connected WPPs	2019	Grid-Connected Wind Power Plants: A Survey on the Integration Requirements in Modern Grid Codes	Wu et al.
[15]	Microgrid and DERs	2021	Microgrid and Distributed Energy Resources Standards and Guidelines Review: Grid Connection and Operation Technical Requirements	Rebollal et al.
[16]	Spanish PVs	2022	Evaluation of the latest Spanish Grid Code requirements from a PV power plant perspective	Martinez-Lavin et al.
[17]	Small-scale PVs	2020	Grid integration of small-scale photovoltaic systems in secondary distribution network – a review	Panigrahi et al.
[18]	ESSs	2018	Review of voltage and frequency Grid Code specifications for electrical energy storage applications	Luo et al.
[19]	Voltage requirements on LV and MV	2022	Voltage regulation regulations for LV and MV	IREC
[20]	RESs	2022	Grid codes for renewable powered systems	IRENA
[21]	MVDC	2022	Medium voltage DC distribution systems	CIGRE
[22]	HVDC	2021	A comparison review on transmission mode for onshore integration of offshore wind farms: HVDC or HVAC	Rahman et al.
[23]	EVs	2020	Electric vehicle standards, charging infrastructure, and impact on grid integration: A technological review	Das et al.

[24]	EVs	2022	Milestone 10 "Recommendations for electric vehicle integration"	Nacmanson et al.

The full range of GCs and standards covered by the review of the documents mentioned above are depicted in Table 3. Standards are included in the reviewed data as they serve to inform the development of the GCs. The following sections discuss the specific requirements of these GCs and standards, while additional detail of the requirements can also be found in Section 10.1 or in the GC Specifications excel sheet that is currently available to all of the iPLUG partners.

Table 3 Reviewed grid codes and standards and their applications

Reference	Region	Grid code	Standard	Title	LV	MV	Power (S or P) and current ranges	Application
[29]	AT	x		(Hauptabschnitt) D4 2.3	x	x		DGs
[30]	AU			ADVANCED INVERTERS				GFM inverters
[31]	AU/ NZ		x	AS/NZS 4777.1			≤200 kVA	Inverters
[32]	AU/ NZ		x	AS/NZS 4777.2	x			Inverters
[33]	California	x		Rule 21	x	x		DGs
[34]	CN		x	GB-T 19964	x	x		PVs
[35]	CN		x	GB-T 20046	x		≤10 kVA	PVs
[36]	DE		x	BDEW		x		DGs
[37]	DE		x	VDE-AR-4105	x		≤100 kVA	DGs
[38]	DK	x		TECHNICAL REGULATION 3.2.2		x	>11 kW	PVs
[39]	DK	x		TECHNICAL REGULATION 3.3.1	x	x		Batteries
[40]	EC	x		ARCONEL 003	x	x	<100 kW	PVs
[27]	EU	x		2016/1447				HVDC

[41]	EU	x		CLC/TS 50549-1	x		>16 A	DGs
[42]	EU	x		CLC/TS 50549-2		x		DGs
[43]	EU		x	EN 50160	x	x		AC networks
[44]	EU		x	EN 50438	x		≤16 A	DGs
[45]	EU		x	IEC 61000-2-2	x			EMC of power supply devices
[46]	GB		x	1467	x	x		EV smart chargers
[28]	GB	x		DN GC	x	x		Connecting to DN
[47]	GB	x		G59		x	<17 kW per phase or <50 kW 3 phase	DGs
[48]	GB	x		G83	x		<16 A per phase	DGs
[25]	GB	x		GC0137 (ECC 6.3.19)				GFM inverters
[49]	GB		x	Gov Regulations	x	x		EV smart chargers
[50]	IN		x	GAZETTE OF INDIA PART 3 SEC.4	x		≤100 kVA	DGs
[51]	Int.		x	IEC 61727	x	x	<10 kW	PVs
[52]–[54]	Int.		x	IEC 62898-1; -2; -3-1	x	x		AC systems with loads and DERs
[55]	Int.		x	IEC/IEEE/PAS 63547			≤10 MVA	DERs
[56]	Int.		x	IEEE 1547	x	x	<10 MVA	DGs
[9]	Int.		x	IEEE 1547.9	x	x	<10 MVA	ESSs
[57]	Int.		x	IEEE 929			<10 kW	PVs

[58]	Int.		x	IEEE P2030.8				Microgrid controllers
[59]	Int.		x	UNE/EN/IEC 62109			≤1 kV	PVs
[60]	IT	x		CEI 0-16		x		Power supply devices
[61]	IT	x		CEI 0-21	x			Power supply devices
[62]	PR		x	MTR				WTs and PVs

4.3 Grid code requirements: overview and examples

The review of the GCs mentioned above highlights the importance of the following fields to allow converter interfaced devices to connect to the grid:

- Interconnection requirements
- Operating conditions
- Control capabilities
- Grid services (differentiated from Control capabilities as those which require high energy density and may not be achievable with limited/uncontrollable energy sources associated with renewable generators)
- Power quality
- Protection capabilities
- Intentional island operation and microgrid performance

Sections 4.3.1 to 4.3.7 overview these specifications that converter interfaced energy sources are subject to, while Section 4.3.8 discusses the different requirements for devices that regularly consume energy.

4.3.1 Interconnection requirements

4.3.1.1 Measurement configuration

Measurements need to be taken to ensure the converter devices can track the conditions of the system they connect to and can adapt their operation accordingly. Some GCs and standards specify the location and type of measurement that needs to be taken (detailed in Table 4). The measurements are either specified to be taken at the point of common connection/coupling (PCC), defined as the interface where the device connects to the network, or the point of connection (POC), defined as the output of the device. All of the GCs require phase to neutral (Ph2Neu) measurements apart from the International standard for DERs (with a capacity less than 10 MVA) [43] that requires phase to phase (Ph2Ph) measurements. Wherever specified, all of the standards are applicable to both single and three-phase systems.

Table 4 Reference measurement requirements

GC/Standard	Location of measurement	Type of measurement	Applicable systems
BDEW	PCC	Ph2Neu	
VDE-AR-N 4105	PCC	Ph2Neu	1 & 3Ph
GAZETTE OF INDIA PART 3 SEC.4	PCC		
CEI 0-21	PCC		1 & 3Ph
GB-T 19964	PCC/POC		1 & 3Ph
IEC 62898-1	POC		
IEC/IEEE/PAS 63547	PCC/POC	Ph2Ph	1 & 3Ph
G59		Ph2Neu	1 & 3Ph
G83		Ph2Neu	1 & 3Ph
UNE 206007			1 & 3Ph
AS 4777.2		Ph2Neu	
EN 50438		Ph2Neu	
DK 3.3.1	POC		

4.3.1.2 Pre-connection requirements

Three GCs and standards define the acceptable voltage source properties that a converter must have, within ranges around the grid's voltage properties, to ensure its reliable operation. The IEEE standard 1547 for DERs [56] and California's requirements for generation connecting to the distribution network (DN) [33] expect the converter to maintain voltage phase, frequency, and magnitudes within 20 deg, 0.3 Hz (0.5 %), and 10% of the grid's voltage, respectively, to allow connection.

So long as the devices meet the voltage property pre-connection requirements, several GCs define a connection/ reconnection delay that devices must observe before connection. The grid's properties must remain within acceptable ranges (defined in Section 4.3.1.2) throughout this delay period to ensure the safe operation of the device and allow connection. The delays range from 20 to 300 s and are detailed in full in Table 5.

Table 5 Reconnection delay requirements

GC	CLC EN 50549	G83	CEI 0-21	GB-T 2004 6	VDE-AR-N 4105	DK 3.3.1.
Reconnection delay (s)	60	20	60	20 to 300	60	180

The recent update to IEEE 1547 to account for the capabilities of ESSs also mentions some additional considerations that must be made. In some cases the ESS may only be allowed to charge from an associated (local) energy source [14]. Therefore, the specific charging arrangement needs to be agreed and is an additional requirement prior to connection.

4.3.2 Operating ranges

Regions of mandatory operation are defined by SOs to ensure that devices can operate continuously and predictably during the expected and standard system conditions. Frequency ranges need to be consistent across a synchronous area, whereas, voltage ranges can vary locally. The limits of the standard voltage and frequency operating conditions are defined as the inner range boundaries in terms of a percentage deviation from the corresponding base values. Outside of this range devices are generally allowed to disconnect following a given delay period. It is also quite common for the GCs and standards to define a second operational range (defined as the outer range boundaries hereon) outside of which the disconnection delay is reduced to enable devices to disconnect sooner from more extreme variations.

Table 6 and Table 7 detail the least stringent, average, most common (mode), and most stringent voltage and frequency operating ranges and disconnection delay settings. The values do not represent a single GC but instead the statistical representation of a given setting e.g. most stringent lower boundary is -30% and the most stringent lower delay is 35 s, not that the most stringent GC has a lower boundary of -30% and a lower delay of 35 s. Table 25 and Table 26 provide the full details of the voltage and frequency operating conditions for all of the reviewed GCs and standards.

More documents provide detailed inner and outer voltage ranges than frequency ranges, which are more regularly defined in terms of an inner range only. Table 6 depicts a clear trend in the most common voltage delay period, reducing from 2 s to 0.16 s for more extreme voltage variations. The limits of the inner and outer ranges commonly extend lower for undervoltages compared to overvoltages. Table 7 shows that devices are commonly allowed to disconnect after only 0.1 s beyond the limits of the inner frequency range, however, more stringent (longer connection) requirements are observed up to 600 s for underfrequency and 300 s for overfrequency events. The few GCs that define outer frequency ranges are often associated with low stringency inner boundaries. The outer boundaries of these GCs and Standards often resemble closely with the single frequency boundaries defined in the remaining documents (Table 26). This provides a clear indication of the maximum frequency deviations that a converter would be expect to endure. In general, the disconnection thresholds are more stringent (asked to remain connected for larger variations and longer durations) for devices on small isolated systems to ensure they survive the more regular and severe frequency variations.

Importantly, the final frequency threshold needs to be aligned with underfrequency load shedding settings to avoid the disconnection of generation before load [20].

Table 6 Voltage operating range statistical overview. The asterisk* marking indicates that the corresponding least and most stringent settings are observed more than once throughout the grid codes

	Inner range				Outer range			
	Lower boundary	Lower delay	Upper boundary	Upper delay	Lower boundary	Lower delay	Upper boundary	Upper delay
Least stringent	-3%	0.1 s	5%*	0.1 s*	-8%	0.1 s*	6%	0.03 s
Mean	-16%	4.48 s	11%	32.29 s	-39%	0.4 s	20%	2.31 s
Mode	-12%	2 s	10%	2 s	-50%	0.16 s	20%	0.16 s
Most stringent	-30%*	35 s	20%*	603 s	-60%	2 s	37%*	31 s

Table 7 Frequency operating range statistical overview. The asterisk* marking indicates that the corresponding least and most stringent settings are observed more than once throughout the grid codes

	Inner range				Outer range			
	Lower boundary	Lower delay	Upper boundary	Upper delay	Lower boundary	Lower delay	Upper boundary	Upper delay
Least stringent	-0.2%	0.1 s*	0.2%	0.1 s*	-5.0 %*	0.16 s*	3.0% *	0.16 s*
Mean	-3.1%	56.9 s	2.1%	52.6 s	-5.4 %	0.48 s	3.3%	0.28 s
Mode	-5.0%	0.1 s	0.8%	0.1 s	-5.0 %	0.16 s	3.3%	0.16 s
Most stringent	-6.0%*	300.0 s*	4.0% *	300.0 s*	-6.0 %	2.05 s	4.0%	0.55 s

4.3.3 Control capabilities

GCs require devices to possess different control capabilities to ensure that the grid's stability can be supported and maintained. Two categories of control capability are often required. Conventional control capabilities are necessary for most devices to ensure that the grid's voltage and frequency conditions are maintained during normal conditions and undesired events are minimised as best as possible during extreme conditions. The capabilities have previously been expected more of larger devices connected to medium and higher voltage levels but are increasingly being asked of small devices on low voltages [20]. These control capabilities are not expected to require any additional energy source beyond the converter interfaced device itself.

Additional control capabilities associated with the conventional stability phenomena are increasingly required due to the displacement of synchronous generators (SGs). These capabilities are beginning to be sourced from converters. These control capabilities can be considered to be supplementary to the mandatory capabilities, although they are critical for systems experiencing significant increases in the penetration of converter interfaced devices or for microgrids. It is possible/likely that these additional control capabilities will require additional power and energy capacity than that available to renewable energy sources, hence their consideration as supplementary services to the grid.

The conventional mandatory control capabilities that will be expected of most/all converter interfaced devices in the coming years will be discussed in the following parts of this Section, while the additional capabilities that might be considered supplementary/services will be discussed in Section 4.3.4.

4.3.3.1 Voltage and reactive power control

The reviewed GCs generally require the converter interfaced devices to be capable of operating in a range of voltage control modes to ensure that the devices can be effectively integrated into the power system without degrading the voltage profile. The exact specifications are often determined according to the reactive power capability of the specific energy source and the feasibility to deliver different modes [20]. The expected control modes identified throughout the reviews are:

- Voltage-reactive power (V-Q) mode – where reactive power is adapted according to the grid voltage. A specific range of reactive power capability is often defined that varies depending on the grid voltage conditions. Although this control mode is most commonly expected of devices on higher voltage networks, an example V-Q operating range defined for DERs in IEEE 1547 is pictured in Figure 18.

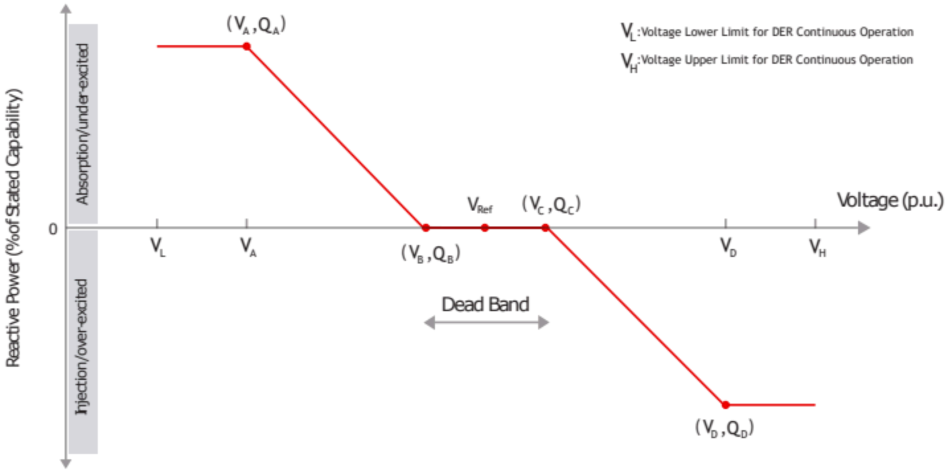


Figure 18 V-Q control capability defined for DERs in [56]

- Fixed PF mode – where a given PF is achieved within a given period and maintained as instructed by the SO, irrespective of the system conditions, but within the device's agreed PF capability range. IEEE 1547 states that this should be the default operating mode for DERs [56]. The PF capability range is generally defined as capacitive and inductive PF limits, although the expected operational ranges can be defined for particular power transfer levels, or as a function of power transfer. The full range of PF limits is detailed in Table 27. The most demanding PF ranges identified in the review expect devices to achieve operation between 0.85 inductive to 0.85 capacitive PFs, however, the most common limits are between a capacitive PF of 0.9 and an inductive PF of 0.95. Figure 19 exhibits an example of the PF capability expected of ESSs in Denmark between 0.9 capacitive and 0.9 inductive.

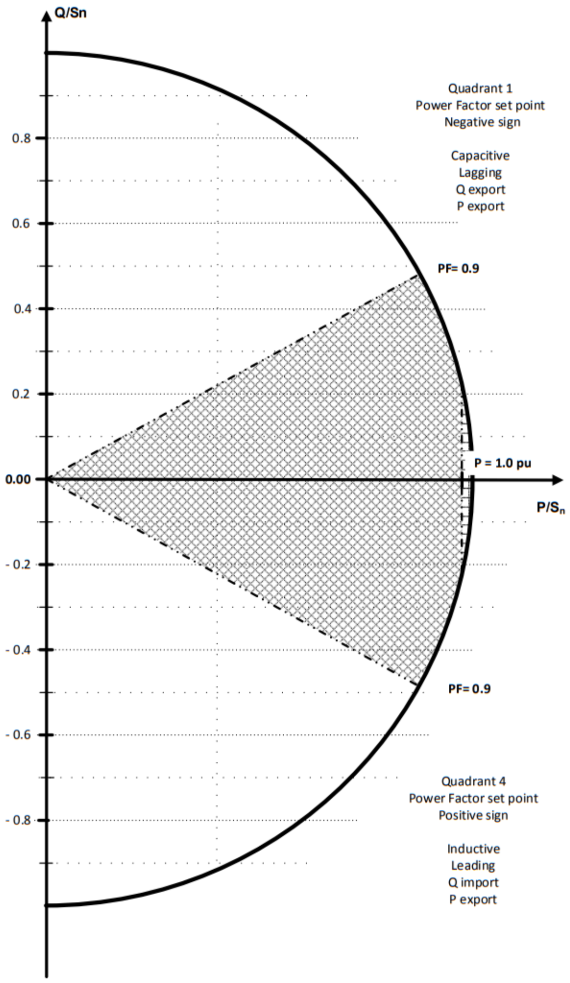


Figure 19 Power factor capability requirement for ESSs detailed in [39]

- PF-active power (PF-P) mode – where the device's PF is varied as a function of its active power transfer. This control mode is more common for low voltage applications. In some cases, this control mode is only required to be activated at certain voltage levels. For example, the Danish GCs for small PVs [38] and batteries [39] both ask that PF-P mode is activated at V=1.05 PU and deactivated at V=1 PU.
- Voltage-active power (V-P) mode – where active power is varied (limited) in response to grid voltage fluctuations.
- Reactive power (Q) control – where the reactive power is varied irrespective of the device's active power transfer or the grid's voltage conditions but within the agreed reactive power capabilities. An example of the required capability that an ESS is expected to be able to achieve in the recent update to IEEE 1547 is pictured in Figure 20.

Some of the standards specify delivery timescales for the different services. [39] asks ESSs to be able to implement the full PF-P or Q control response to changes in the corresponding setpoint within 10 s, while the German GC for generation connecting to the MV network requires a full control response to PF-P setpoint changes within 10 s but asks that the V-Q setpoint change is delivered within 10s and 1 minute [36].

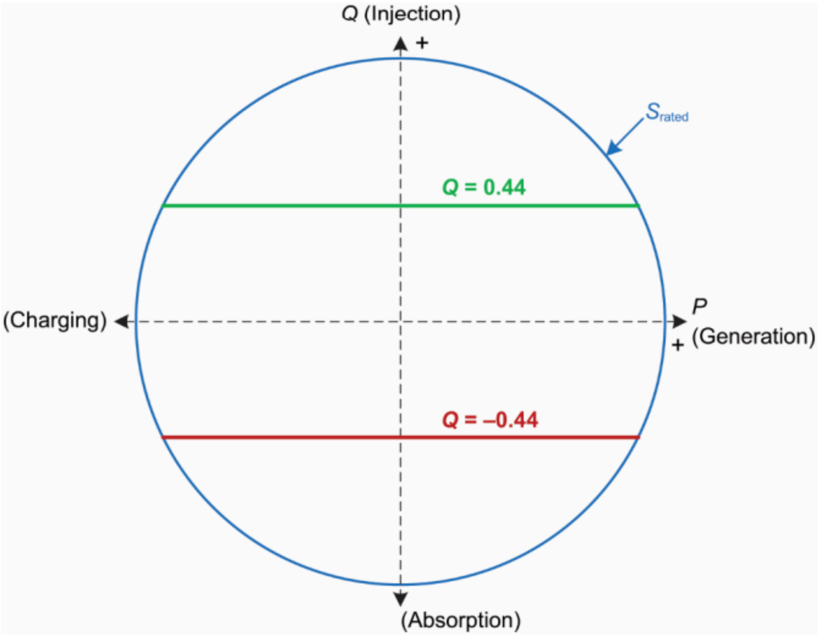


Figure 20 Reactive power capability expected of ESSs in [26]

4.3.3.2 Voltage ride-through

Although voltage ride-through (VRT) requirements can be more detailed for devices connected at higher voltages, many distribution network GCs define a time-domain voltage profile that, above which, devices should remain connected throughout. The profile defines extreme voltage conditions that converters should endure following a fault and is used to ensure predictable device behaviour and therefore system resilience. The requirements should be fine-tuned to balance the device capability and the system stability. For example, although inverters are less capable to provide overcurrent during a fault they are more flexible and can be asked to provide ride-through profiles unconstrained by the physical properties of a SG [20]. The full range of GC settings are defined in Table 28, where the voltage magnitude and time values relate to the corresponding points indicated on Figure 21. Figure 21 is an example of the ride-through requirements defined for generators on LV networks in the European standard [41].

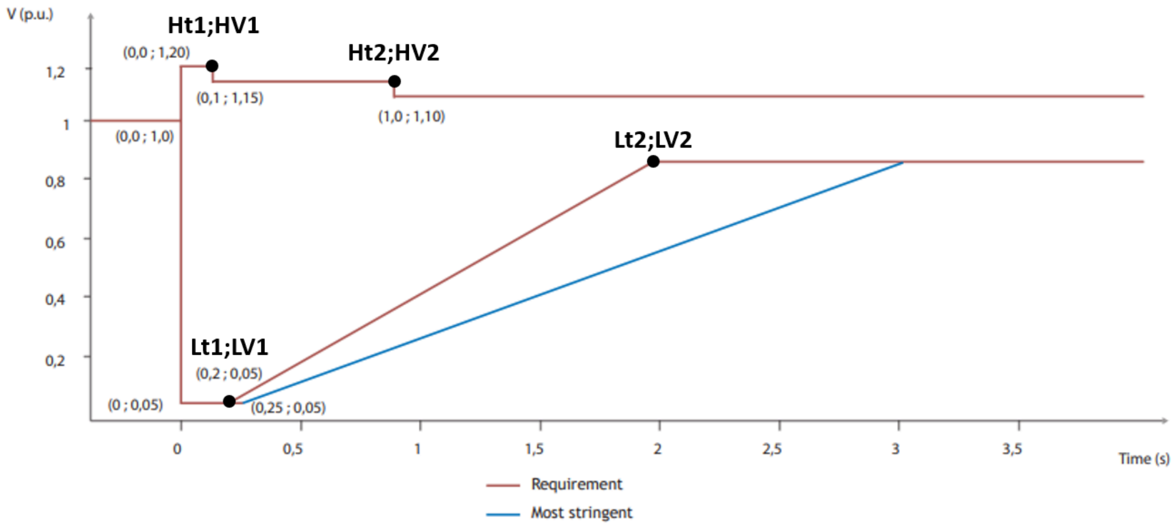


Figure 21 Voltage ride-through requirements for generators with rated current greater than 16 A connecting to European LV networks [41]

In general, a minimum operational envelope is defined so that if the voltage exceeds any given time-dependent level the device can disconnect. Within the envelope the device must remain connected. Profiles are defined for both under- and overvoltage conditions, but the exact voltage levels and critical time periods vary between the GCs. Some GCs specify that the devices must be able to withstand a voltage drop to 0 V, while the largest overvoltage that devices are asked to withstand is 1.4 PU (specified by the Puerto Rican GC for wind turbines (WTs) and photovoltaic generators (PVs) [62]).

The Danish GC for PV on MV networks [38] and for ESSs [39] also defines voltage phase jump and ROCOF limits that the devices must be able to ride through (20 deg and ±2 Hz/s (4 %), respectively), outside of which disconnection can occur following a delay of 0.1 s. Moreover, the Danish GCs are the only documents identified in the review that specifically define a ride-through requirement for devices in response to unbalanced faults. The GCs state that devices must remain connected to the system for 0.15 s following 3 phase, phase-to-phase-to-earth, and single phase faults [38], [39]. The GB GC update states that GFMs should be able to endure a phase jump of 90 deg to ensure its ability to support the grid voltage [25].

4.3.3.3 Reactive current provision/ Short Circuit Current

Reactive current provision relates to the current response of a device/system following a short circuit fault. Conventionally, SGs have provided significant Short Circuit Current (SCC) due to their overcurrent capability and voltage-source behaviour. The high SCC capability has driven the development and use of protection procedures that identify faults using abnormal current flows, generally known to be sourced from the transmission network. However, the displacement of SGs on the transmission network has resulted in the decrease in SCC levels. Moreover, this displacement is generally associated with an increase in the penetration of converters (and their associated energy sources) on lower voltage levels, which furthers complicates the operation of the protection systems.

The different system needs result in different approaches and requirements for Reactive current/SCC provision. On transmission systems, the SOs prefer plants to provide fault current to minimise the voltage dip and support system stability. This requirement would generally be defined as some kind of reactive/active/hybrid current injection [20]. Three approaches are generally observed on transmission systems where the provision is more conventional: 1) the prioritisation of reactive over active current (more common in larger systems that aim to isolate the fault), 2) the prioritisation of active over reactive current (more common in smaller systems that are more sensitive to potential frequency variations, and 3) a hybrid approach that enables a balance between active and reactive current capability [20].

However, on distribution systems, SOs might prefer that DERs do not disturb the existing protection arrangements so can ask devices not to inject reactive current. For example, the IEC Standard for DERs <10 MVAs [55], IEEE 1547 [56], and the Indian GC for generators connected to the LV network [50] all require devices to cease energisation when SCC begins to be provided in response to a disturbance. Otherwise, devices can be asked to specify their SCC capability to ensure that the protection can be adapted effectively to account for the new generation. This approach is observed in the German GC for devices connected to MV networks [36], the GB GC for devices connected to LV networks [48], and the Italian GC for devices connected to LV networks [61], which all state that the SO and manufacturer/connection owner should agree a maximum SCC threshold that a device can sustain. Often, the standard capability of converters is assumed to be SCC=1 PU [36], [61].

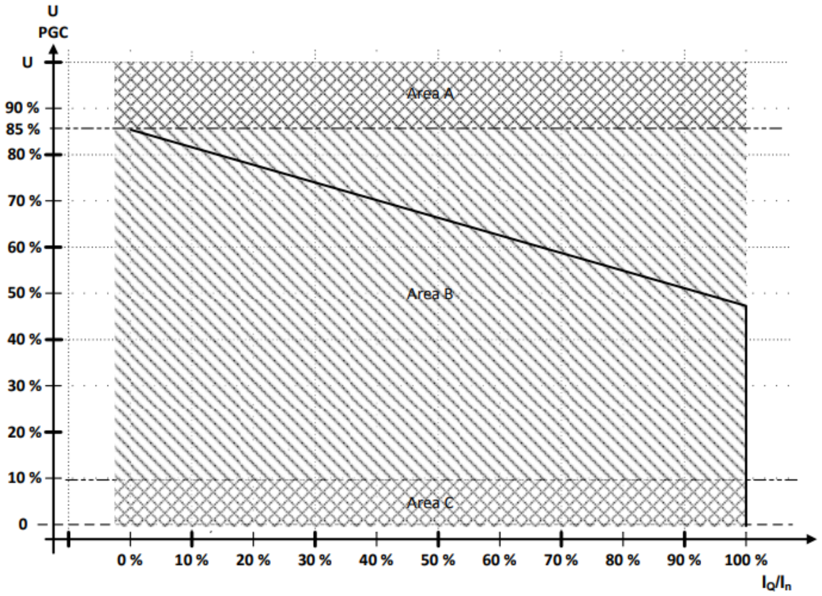


Figure 22 Reactive current-voltage droop slope for ESS reactive current provision [39]

The LV and MV GCs that specify reactive current provision throughout the faulted voltage conditions often describe it in terms of a reactive current-voltage droop slope or gradient equivalent. The Danish GC defines a minimum droop slope that PV devices should achieve/ exceed [DK 3.2.2]. The Danish requirements are similar for ESSs [38], although the droop slope is slightly adapted (pictured in Figure 22). Both slopes ask for full reactive current delivery following around a 50% reduction in grid voltage. The European standard for small generators connected to MV networks ask for a reactive current gradient between 2 and 6 times the voltage change and that the delivery occurs within 30 to 60 ms [42]. The Puerto Rican GC for WTs and PVs defines an envelope of droop slopes (1% to 5%) that devices should operate within

[62]. Reactive current provision in response to faults can also be considered a feature of GFM capability, which is discussed in more detail in Section 4.3.4.1.

4.3.3.4 Frequency regulation

4.3.3.4.1 Overfrequency conditions

Table 8 Frequency regulation requirements

GC	Specific application	Lower boundary (% of f0)	Upper boundary (% of f0)	Droop response (Power % per Hz)	Notes
BDEW		0.4	3	40	
VDE-AR-N 4105		0.4	3	40	
EN 50438		0.4		42	
CEI 0-16		0.6	4	20 to 50	>10 s
CEI 0-21		0.4	3	16.7 to 100	
GB-T 19964		0.4			
CLC/TS 50549-1		0.4	4	16.7 to 100	
DK 3.3.1	In DK1	0.4	3	16.7 to 100	>2 s and <15 s
"	In DK2	1	3	16.7 to 100	>2 s and <15 s

Some control capability to support system frequency is also defined throughout the reviewed documents. The first requirement is the definition of acceptable active power-frequency (P-f) droop regulation, where devices are generally expected to reduce their active power output at a given rate or within some acceptable envelope as frequency increases. These requirements can generally be expected of most energy source types as no additional/significant energy capacity is required to reduce the power output. The range of frequency regulation settings are shown in Table 8.

Many GCs define acceptable droop rates in terms of an active power change (percentage of rated power) per Hz of frequency change. The acceptable droop settings result in a range of power responses: from 16.7 to 100% of the rated power per Hz of frequency deviation, while the most common setting is 40%. The GCs also generally define boundaries where the overfrequency droop regulation should occur, including a lower boundary (deadband) above the base frequency to avoid regular switching of the droop control and an upper boundary at/around the expected limits of the devices' operating range. Only the Italian GC for MV devices and the Danish GC for ESSs define delivery speeds for this frequency regulation.

The Italian SO requires the response to be slower than 10 s [60] while the Danish GC requires ESSs to deliver the regulation between 2 and 15 s [39]. The Danish SO specifically stipulates that DGs (including ESSs) should not initiate the delivery within 500 ms to avoid unintentional islanding [39].

4.3.3.4.2 Underfrequency conditions

Another requirement stipulated by some of the reviewed GCs for limited energy sources ensures that the power output by devices does not reduce beyond a given level when the frequency is below the nominal value. This requirement is included to avoid the exacerbation of the imbalance between generation and demand despite these devices possessing relatively un-controllable energy reserves. The specifications define: 1) an operational frequency range where the support should be delivered and 2) the maximum power reduction rate (PU per Hz of frequency deviation) that is allowed during this range. The ENTSO-E recommendations for generators on LV networks defines an inner range between 49 and 49.5 Hz, where the maximum allowable reduction is 10% per Hz, and an outer range below 49 Hz (but before disconnection), where the maximum allowable reduction rate is tightened to 2% per Hz [41]. The IEEE standard 1547 stipulates that the active power should not be decreased from the pre-disturbance level or 80% of the rated power, whichever is lower, during events where the frequency decreases below 58.8 Hz [56].

4.3.3.4.3 Ramp rate limitations

Outside of frequency disturbed conditions, the Australian GC for DERs [32] and the Danish GC for ESSs [39] both define ramp rate ranges that the converter interfaced devices should achieve or remain within to minimise the effect that rapid power fluctuations have on the network. The Australian GC defines an output power ramp rate limit of ±16.67% and that the signal should not exceed a maximum of 10% nonlinearity content [32]. The Danish GC defines ramp rate limits of ±20% of the device's rated power or a hard limit of 60 MW per minute, whichever is smaller.

4.3.4 Grid services

4.3.4.1 Grid-forming operation

Converter interfaced devices are beginning to be considered for the provision of grid-forming (GFM) control capabilities on the wider electric power system. The GFM controls are desirable due to their ability to provide the robust stability to systems that was conventionally sourced from SGs but is increasingly scarce due to their displacement. However, due to the limited experience of converter-based GFMs on large power systems, the requirements for converters to provide these services have not been defined by many SOs.

Great Britain's National Grid Electricity System Operator (NG ESO) updated their GC, which is outlined in [25], in an attempt to standardise GFM capability. The GFM functionality includes active and reactive control-based power capabilities that are equivalent to the standard power transfer that is achieved by conventional converter interfaced devices, however, this transfer is limited to operate with a bandwidth <5 Hz to avoid undesired interactions with the grid. The conventional control capability is then exceeded with the addition of the following features: phase (angle) response, damping, and inertial active powers, fast fault reactive current, and voltage (magnitude) jump reactive power. All of these additional features are considered to be inherent to the GFM, which operates as a voltage-source, and are therefore expected to either start to respond or achieve full delivery instantaneously (where an instantaneous response time is quantified as <5 ms). The Australian SO provides a similar overview of GFM capability [30], however, the overviews expects inertial active power to be delivered instantaneously, where the NG ESO definition simply expects inertia to initiate within the 5 ms timeframe.

Inertial provision is also mentioned in the IEEE Standard 1547 for DERs [56] and the IEC standard 62898-1 for the operation of LV and MV AC systems [52], although in these cases the potential to provide inertia is simply mentioned and requirements for its provision are not detailed. The recent update to IEEE 1547 to account for ESS capability mentions the lack of established performance criteria for inertia provision that is limiting the ability for SOs to standardise the service [26]. It is also worth mentioning that inertia need not be sourced uniquely from GFMs as grid-followers (GFLs) are capable of providing the same power injections at the same speed, despite conventional assumptions that they are too slow [66]. Overall, this new field of specifications for conventionally inherent stability are in their infancy and therefore requires significant effort to be made more transparent and more effective at procuring useful solutions.

Finally, specific GFM services such as black start capability are mentioned in the NG ESO GFM specification, however, the requirement to provide such a service simply depends on the plant's proven ability to provide the above mention GFM functionality [25]. The updated IEEE Standard 1547 that considers ESS capability also mentions that devices aiming to participate in black start may agree both a wider range of acceptable voltage and frequency operating conditions and a wider range of allowable ramp rates or power steps while participating in the service [26].

4.3.4.2 Frequency services

Converter interfaced devices, particularly battery systems, are increasingly being used to provide rapid primary frequency services, thanks to their fast delivery speeds. These services are often termed fast frequency responses (FFRs). The service requires a device to deliver an active power injection or absorption in response to a given magnitude of frequency deviation. The faster delivery speed compared to conventional primary frequency services allows the frequency deviation to be contained better and can support low inertia systems to maintain frequency stability by limiting the rate of change of frequency (ROCOF).

Some systems around the world have developed FFR type services, particularly those with large penetrations of converter interfaced devices. Table 9 details the specification of the identified FFR services in terms of the deadbands that the service cannot operate within, the speed at which the active power injection should be delivered in full, and the duration that the support is expected to be sustained. The fastest mandatory delivery speed is 0.7s, which is required for frequency deviations >500 mHz on the Nordic system.

As well as the information in Table 9, some SOs describe the recovery and reactivation criteria for the FFR service. The Finnish SO states that the recovery period can begin from either 15 s after the disturbance or immediately after the agreed mandatory delivery duration, whichever value is larger [67]. During this recovery, the power absorbed cannot exceed 25% of the agreed FFR capacity. The Finnish SO also states that any qualifying device must be able to reactivate the same FFR service within 15 minutes of its last activation [67]. This requirement is echoed by the Australian SO [68]. Finally, the Irish SO specifies that a device can only qualify to provide FFR if it can ensure that the energy delivered during that activated FFR period from 2 to 10 s is greater than the energy absorbed during the deactivated FFR/recovery period from 10 to 20 s following the disturbance [69].

Table 9 Fast frequency service specifications. * indicates a service duration if the power deactivation rate is ≤20% of the FFR capacity per second.

Reference	Region	Standard / service	Deadband (mHz)	Full delivery speed (s)	Service duration (s)	Reference
[26]	International	IEEE 1547.9		>0.2	10	[26]
[69]	IE	FFR - dynamic	±15 to 200	<2.0	>8	
"	"	FFR - static	±200 to 700	<2.0	>8	
[67]	Nordic system	FFR	-300	<1.3	>5* else >30	
"	"	"	-400	<1.0	>5* else >30	
"	"	"	-500	<0.7	>5* else >30	
[68]	AU	FFR		<1.0		
[70]	GB	Dynamic containment	±15	>0.5 & <1.0		

4.3.5 Power quality

4.3.5.1 Harmonic content

The maximum harmonic content of a converter's output is a common requirement on LV and MV networks to ensure that the system's current and voltage waveforms are not unnecessarily distorted (to avoid additional losses and the mis-operation of the network's protection system). Harmonic and intraharmonic content from converters is also known to resonate with other components on the system that can result in oscillatory interactions and potential instabilities [20]. The allowable harmonic content is specified in terms of a distortion limit as a percentage of the rated current or voltage or as a current amplitude limit per MVA of generating capacity. The limits are defined for individual or a range of harmonics, where smaller odd harmonics are generally the most critical and therefore most thoroughly specified. The harmonic limitations defined in the reviewed GCs are shown in

Table 29 and Table 30.

4.3.5.2 Permissible imbalance

The permissible imbalance for converter outputs are defined in several of the reviewed GCs to minimise the undesirable imbalance between the 3 phases of an AC system. The current imbalance between any phases should not exceed 16 A according to the GB GC for small generators connected to the MV network [47] and the Danish GC for ESSs [39], while this limit is relaxed to 21.7 A (or 5% of the output) at rated power according to the Australian and NZ GCs for inverters on LV networks [32]. Power imbalance between phases is defined in some GCs, where the GB GC imposes a limit of 17 kW difference between phases [47] and the German GC for DERs on LV systems imposes a limit of 4.6 kW [37].

4.3.5.3 Direct-current content

The maximum allowable DC current content injected to the AC power system is regularly defined in LV and MV GCs. The limitation is normally defined as a percentage of the device's rated current. The most common DC current limit is 0.5%. The full range of settings identified in the review is detailed in Table 10.

Table 10 Maximum DC current content requirements

GC	G 59, G 83	AS 4777.2, CEI 0-21, IEC/IEEE/PAS 63547, IEEE 929, UNE 206007-1, GAZETTE OF INDIA PART 3 SEC.4, EN 50438, UL 1741, IEEE 1547, RULE 21, DK 3.3.1	GB-T 20046	VDE-AR-N 4105
Maximum DC current	0.25 %	0.5 %	1 %	1 A

4.3.5.4 Voltage fluctuations

Voltage fluctuation limits are also defined in some GCs to minimise the amount that periodic voltage variations increase as a result of the integration of converter interfaced devices. The voltage fluctuation limit can be defined in terms of a short (10 minute period) or long (2 hour period) flicker, where the flicker is calculated as an average across either period and relates to the flicker of lights. Alternatively, the voltage variation can be defined as a rapid fluctuation and a limit is generally defined as a percentage of the time that fluctuations of a given magnitude must not exceed. Finally, absolute magnitude limits are also imposed by some GCs. The most common absolute limit of voltage fluctuations imposed by the given device is 5%. The full range of voltage fluctuation limitations is shown in Table 11.

Table 11 Voltage fluctuation requirements. * indicates requirements for either a single ESS/ pair of ESSs/ or more ESSs

GC	Specific application	Short term flicker	Long term flicker	Rapid fluctuations	Absolute fluctuation limit (%)
IEC/IEEE/PAS 63547					5
BDEW			0.46		2
VDE-AR-N 4105			0.5	one fluctuation beyond 3% every 10 mins	3
G83			0.65		
IEEE 1547	MV			<3% of time beyond 3%	5
"	LV			<5% of time beyond 5%	
DK 3.3.1	>1 kV	0.3	0.2		4
“	<1 kV	0.35/0.45/ 0.55*	0.25/0.30/ 0.40*		
Rule 21					5
ARCONEL 003					5
GAZETTE OF INDIA PART 3 SEC.4					5
AS 4777.2					2

4.3.5.5 Leakage current

Only the German GC for DERs connected to the LV network defines a limitation for leakage current, which is a significant issue for non-isolated converters. Clearing times are defined that different average leakage current magnitudes should be removed from the system within, all of which are detailed in Table 12.

Table 12 Leakage current requirements

GC	Average leakage current (mA)	Clearing time (s)
VDE-AR-N 4105	30	0.3
〃	60	0.15
〃	100	0.04
〃	300 (peak)	0.3

4.3.6 Protection requirements

4.3.6.1 Grounding and galvanic isolation requirements

Grounding is an important requirement for electric devices to avoid electric shock from equipment and overvoltage risks on systems during fault conditions. Grounding via a neutral line is common for medium and higher voltage levels. The neutral line provides a path for fault currents to pass through that allows the monitoring of system conditions for protection and can reduce the magnitude of the current using additional resistance. Alternately, low voltage systems are sometimes earthed directly, known as solid earthing.

Galvanic isolation describes the electrical separation within a device, often achieved using an electromagnetic connection stage. Isolated devices possess inherent fault blocking capability and allow different voltage levels to be interconnected easily [21]. For example, an isolated device connecting LV & MV voltage levels would allow the two sides to be designed independently and optimally. However, non-isolated converters offer cost savings in terms of semiconductor and transformer components.

The Ecuadorian GC for PVs<100 kW requires them to be fitted with a single independent grounding system and to achieve galvanic separation from the network [40]. European standards recommend that earthing arrangements for generators connected to the LV [41] and MV [42] networks should comply with specific national legislations. The GB DN GC requires generators on MV levels to follow ENA TS 41-24 and that they must agree with the DNO to ensure that the configuration is compatible with the existing system, whereas, generators on LV levels are required to follow DPC7.4 [47]. These LV generators also have the option to either use the terminals provided by the DNO or an independent system. The IEEE Standard 1547 states that any grounding scheme shouldn't prevent the effective operation of the ground-fault protection or drive overvoltages beyond equipment capabilities [56]. The US GC for DERs simply defines a maximum impedance $Z_{max} = 0.1\,\Omega$ that grounding schemes should not exceed [65].

4.3.6.2 Islanding detection

Sufficiently large disturbances can separate large systems into isolated parts. DERs can find themselves separated from the transmission network and its associated SGs during these events. Islanding detection is used to identify this isolation.

Following the detection of isolation, disconnection is often necessary as the DERs would otherwise find themselves responsible for a portion of the system that they might not be capable of supporting. Without this disconnection, their continued operation would likely damage the DER.

The detection is often carried out using a ROCOF margin, outside of which the DER is deemed to be isolated. The GB SO previously implemented a vector shift isolation detection procedure, however, this approach has been abandoned for new generation due to the identification of its mis-operation during disturbed voltage conditions.

It is also important that the distributed devices do not trip undesirably, which has occurred on power systems around the world and resulted in significant unnecessary DER disconnection that drives further system failure [71], [72]. As a result, islanding detection schemes are being adapted to incorporate a trip delay. The delay briefly allows the disturbed conditions to be resolved or return to acceptable levels before the DER(s) is forced to disconnect. All of the identified islanding detection requirements are detailed in Table 13.

Table 13 Islanding detection requirements

GC	Scheme	Limit	Delay (s)	Notes
G59	ROCOF	1 Hz/s	0.5	
"	VECTOR SHIFT	9 deg		Decommissioned for new gen
G83	ROCOF	1 Hz/s	0.5	
"	VECTOR SHIFT	12 deg		Decommissioned for new gen
UL 1741	ROCOF	0.5 Hz/s		
ARCONEL 003				Disconnect if lacking power flow
IEEE 1547	ROCOF	0.5/2/3 Hz/s	2	Variable limit according to desired robustness
IEEE 1547.9	ROCOF	0.5/2/3 Hz/s	2	Consider extending delay to 5 s if providing inertia

4.3.7 Intentional island operation

Additional requirements for devices that plan to operate in island/microgrid conditions have also been specified in some of the reviewed GCs. Many/all of the previously discussed requirements are likely to be needed to support the operation of an energy island, however, the development of these islanded specifications is relatively immature, so the requirement definitions can vary quite significantly. The IEEE Standard 1547 for DERs [56], the US GC for DERs [65], and the Italian GC for

LV devices [61] all define updated voltage and frequency conditions that microgrid capable devices should be able to operate across (shown in Table 14). The IEEE Standard that accounts for ESS capability also considers relaxing the tripping delays for devices that plan to serve loads through islanded operation [26]. The international standard for LV and MV AC systems requires ESSs to be able to support stable system operation while also being able to fully operate their protection equipment [54].

Other documents include less quantitative discussions of the desired functionality from devices that operate in isolation. The German GC for MV-connected devices simply states that any capable generators should support microgrid operation. The GB standard for generators connected to MV networks mentions that further studies are required to ensure the safety, stability, and power quality of microgrids [47], while the international standard for DERs states that microgrid capable functionality will be considered in the future [55].

Table 14 Islanded microgrid voltage and frequency operating ranges

GC	Voltage lower boundary (%)	Voltage upper boundary (%)	Voltage trip delay (s)	Frequency lower boundary (%)	Frequency upper boundary (%)	Frequency trip delay (s)
CEI 0-21	-15	10		-5	5	
UL 1741	-10	10		-1.7	1.7	
IEEE 1547		Outer upper boundary in Table 25	0.008 to 0.16	Inner lower boundary in Table 26	Inner upper boundary in Table 26	11 to 1000 s

4.3.8 Requirements for energy consuming devices

4.3.8.1 DC interconnectors

DC interconnectors are widely used to achieve power transfer across large electrical distances with increased efficiency compared to AC alternatives. The interconnection is especially efficient at high voltage levels where the current (and hence current associated losses) can be lower for a given power. Therefore, HVDC, links are the primary technology used to transfer power between countries or from distant offshore RESs. The back-to-back converter interface also offers a useful interconnecting stage between electrical areas. Asynchronous or different voltage level areas can be interconnected easily and the flexible converter control can provide similar grid support as converter interfaced generators (provided there is sufficient available energy). As well as the interconnection achieved by HVDC, MVDC links are being proposed as suitable devices to interconnect and provide stability benefits on DNs with lower voltage levels. However, the energy characteristics of interconnectors differentiates them from standard generators. Energy cannot be expected to always flow from the converter into the grid and the available energy capacity on any given side now depends on the aggregated balance between the instantaneous generation and demand of all devices on both sides of the interconnector.

HVDC interconnection is widely utilised on the existing power networks so grid code requirements are relatively well-developed. In contrast, MVDC technologies are not as mature or used, so requirements are less clearly defined. Therefore, the existing HVDC requirements are considered here to identify the kinds of requirements expected of interconnector technologies but the exact values are not included in the review above as they may not be appropriate for the application of interest on LV & MV networks.

In general, HVDC interconnectors are often treated in similar ways as DERs and can be expected to achieve similar voltage and frequency operating ranges as those described above. However, the interconnectors connected on the TN are expected to remain connected for significantly longer periods e.g. voltage inner lower delay (as described in Table 6) of 3600 s [27]. Similar control capabilities to those detailed above are also required of the interconnectors, including: reactive power control capability (expected to be delivered as fast as 20 ms in some cases [22]) and compliance with similar VRT envelopes (although operation is required to be maintained throughout considerably longer voltage recoveries e.g. Lt2=11.5 s (as described in Figure 21) [27] compared to those expected of LV & MV DERs Lt2=1.5 to 3 s in Table 28).

HVDC grid code requirements can vary in comparison to those of DERs due to the different energy characteristics. For example, HVDC systems can be required to agree a range of network SCC conditions to maintain continuous operation across and certain remote-end converter communication and control specifications to ensure the ability to send, receive, and respond to information on both the AC network and/or the remote energy island, including the capability to monitor and inform regarding fault conditions [27]. It is also more common for additional control functions to be expected of the interconnectors that can possess larger aggregated energy capacity than individual generators, including: over- and underfrequency support and GFM/ advanced grid support functions such as voltage support and inertia provision. However, as is the case for the LV & MV DER devices described above, these requirements are less clearly defined and requirements appear to regularly be determined by the TSO depending on specific device capabilities and system requirements [27].

A recent report assessing the feasibility and route to develop MVDC interconnecting/grid solutions highlights some of the additional fields that will need to be standardised to further support their deployment [21]. The proposed collection of offshore RESs will require the establishment of remote AC networks. A main network connecting converter will then be expected to establish the voltage of the DC collection pool/grid that these offshore RESs and other converter interfaced devices interface to. Both of the "voltage establishing" converter applications will require reliable and therefore standardised GFM functionality. It is also suggested that all of the converters connecting to the MVDC pool cold subscribe to DC grid code requirements, while the large converter connecting to the main AC grid could ensure the compliance with the more conventional network specifications.

4.3.8.2 Loads

LV and MV networks were originally designed to serve the medium- and smaller-scale loads that people use throughout their daily lives. It is only with the more recent increase in DERs that focus has been paid to the requirements for devices that generate energy at these levels. Therefore, significant portions of the DN GC is applicable to loads. The GB DN GC [28] is reviewed in this section to highlight the requirements that are expected of loads and may be relevant to MPCs that integrate them.

Often, the requirements for loads (both individual and aggregated) are grouped with those for generators on DNs. The GB DN GC states that, similar to generators, the design of loads must be capable of continuous operation across standard voltage and frequency ranges, not adversely affect the voltage control employed by the DNO or impose unwanted voltage fluctuations on the network ($\leq\pm3\%$ during normal conditions but extended to $\leq\pm10\%$ for infrequent events such as energisation), not degrade the operation of the protection systems implemented by the DNO, and should meet the relevant earthing standards.

Beyond the requirements that are shared with generators, loads are required to declare their load characteristics. On LVs this declaration simply requires information regarding the maximum active or complex power demand, the type and loading of the equipment, and the planned date of connection. On MVs additional planning data (e.g. the point of connection to the DN, single line diagrams, control arrangements, time of peak demand, etc.) can also be required. Demand control is asked of most loads (other than small individual customers), whereby the demand is reduced to balance periods of low generation. The demand reduction can be implemented by one of the following methods: voltage reduction by DNO instruction, demand reduction by TSO instruction, automatic low frequency disconnection, and emergency manual demand disconnection. As such, the load must be capable of receiving and responding to the corresponding reduction signal in an acceptable manner. The specific settings for low frequency disconnection are determined for the given system, for example, less load in the highly RES penetrated Scottish region is disconnected during local frequency deviations compared to load subject to the same deviations in the lower RES penetrated English or Welsh regions.

Demand side services can also be provided by loads to DNs and require additional specifications. The services are defined as either active or reactive power modulations in response to DNO instructions. Units that participate in these services are required to comply with specific operating ranges (V=0.9 to 1.1 PU and frequency ranges indicated in Table 15) and must be able to withstand ROCOFs≤ 1 Hz/s for ≥ 500 ms. The load is configured to disconnect at similar times to generation for underfrequency conditions and after generation for overfrequency conditions (as shown in Table 26) to avoid the worsening of the frequency conditions as best as possible.

Table 15 GB DN GC [28] frequency operating ranges for demand side services

Frequency setting		Requirement
Lower boundary	Upper boundary	
47	47.5	Remain connected for >=20 s
47.	49	Remain connected for >=90 min
49	51	Continuous operation
51	51.5	Remain connected for >=90 min
51.5	52	Remain connected for >=15 min

4.3.8.3 Electric vehicles

Electric vehicles (EVs) are expected to take up a significant portion of the automotive market in the coming years due to their ability to decarbonise transport away from fossil fuels. Two EV technologies, all-electric and plug-in hybrid vehicles, interface with the electric network for charging purposes. The power flow can be either unidirectional from the network into the EV to charge the battery (requiring relatively cheap off-board diode rectifier power conversion) or bidirectional (requiring more expensive off-board AC-DC VSC conversion), which allows EVs to return power and support the grid in times of need. Both configurations generally use a DC-DC conversion stage on-board the EV to control the battery state-of-charge. The charging voltages that the EVs plug into can be classified as either: Level 1 – 110 to 220 V (AC), Level 2 – 220 to 240 V (AC), or Level 3 – 200 to 800 V (fast charging DC) [23]. Therefore, EVs will appear on the (LV and potentially MV) DNs as either controllable loads or effectively as ESSs, depending on their capability. Moreover, as EVs are mobile they will introduce both temporally- and spatially-variable loads that need to be managed.

EV devices are generally standardised for three purposes: to achieve their effective integration to and the continued secure operation of the power system, to achieve acceptable standard charging procedure, and to ensure their safe operation and human interaction. The existing grid integration standards treat EVs as DERs e.g. [26], [65], so they can expect to be subject to similar requirements as the standard operating ranges and basic grid support mentioned in the sections above. The charging standards describe the voltage, current, and power levels, plug socket and connector configurations, and any wireless power transfer requirements. Safety standards then describe the requirements to avoid electric, fire, and life safety risks, which are described in more detail in the supporting document available to iPLUG partners: Safety Standard Review.

The UK is perceived to be one of the leading countries in terms of EV standardisation. As of April 2022, all chargers are required to be smart, which is thought to be critical for the use of reflective network tariffs and hence the cost-effective integration of EVs without increasing the strain on DNs [24]. The UK uses legislation underpinned by EU regulations [46], [49] that stipulates the charge point configuration, the use of smart cables (capable of sending and receiving information) that support smart functionality, interoperability between electricity suppliers, and safety provision. The legislation is implemented to operate alongside additional standards [73] that specify vehicle-to-grid communication interfaces and therefore supports the development of additional EV services in the future.

In a roadmap for the deployment of EV capacity on Australia, [24] highlights that international standards need to be used in the short term (but without imposing tight constraining requirements that could limit some technologies) to reduce the cost and increase the options for the rollout of EVs. Following the initial roll-out, it is suggested that local services from EV to grid are implemented in the medium term, and increased to become wide-spread alongside a market for demand reduction in the long term [24]. The success of these approaches relies on the use and development of existing standards to 1)harmonise charging procedures between different suppliers and approaches (e.g. AC vs DC) [23] and 2) evolve as EV penetration increases and technologies mature, providing the opportunity to ease grid constraints instead of simply adding to peak demands.

4.4 Relevant safety standards

This section of the review assesses safety standards that aim to establish terminology, minimum requirements for coordination of converter components, minimum requirements for the converter itself, and requirements to reduce a range of relevant hazards to achieve safe selection, deployment, and operation of power converter equipment. The review is founded on the IEC Standard 62477-1 for general converter applications at low voltage (LV) levels [74], which is described as a basis for power converter applications (with rated voltage $V_{AC} \leq 1000\,V$ or $V_{DC} \leq 1500\,V$) such as interfacing solar, wind, tidal, fuel cell, or other similar energy sources to the grid. This fundamental safety standard is reviewed in detail to identify the critical requirements for converter systems. The report details these requirements on a high level to provide guidance on the fields that should be considered and to direct users to the appropriate sections of the standards, without repeating the exact details that can be found in the standard itself. The foundational standard is then compared with safety standards for different converter applications to assess if there are any significant differences in the requirements. The additional safety standards include: 62477-2 for general converter applications at medium voltage (MV) levels (with rated voltage $1\,kV \leq V_{AC} \leq 36\,kV$ or $1.5\,kV \leq V_{DC} \leq 54\,kV$) [75], 62040-1 for uninterruptible power systems (UPSs) (with rated voltage $V_{AC} \leq 1000\,V$ or $V_{DC} \leq 1500\,V$) [76], and 61400-7 for converter systems that interface wind turbines (WTs) to the grid (with rated voltage $V_{AC} = V_{DC} \leq 36\,kV$) [77].

The findings are detailed in the following three sections, each of which represent a different field of requirements within the standards: Section 4.5.1 describes the requirements to prevent specific hazards, Section 4.5.2 describes the test requirements and procedures to prove the converter system compliance with the requirements from Section 4.5.1, and Section 4.5.3 describes the requirements for information and marking that should be made available with the systems to enable their safe choice and operation.

4.5 Safety requirements

4.5.1 Hazard prevention requirements

4.5.1.1 Fault and abnormal conditions

All of the reviewed standards state that the design of power converters should avoid operating modes or sequences that can cause fault conditions or component failures that lead to hazards. Otherwise, alternate measures must be taken to prevent the hazard. Fault conditions are generally considered to be internal faults within the converter device [77].

The standards require circuit analysis and other testing (detailed in the standards) to determine if the failure of a given component would result in: impact on the decisive voltage determination, risk of electric shock (due to degradation of basic protection/fault protection), risk of energy hazard, risk of thermal hazard, risk of mechanical hazard, electromagnetic force and thermal hazard. This testing is compulsory unless analysis can conclusively show that no hazard will result from the component’s failure. Alternately, components that are tested on and meet the relevant product standards (in similar operational conditions) do not need further analysis.

The testing should be carried out to account for the expected stress during the converter system's lifetime. Therefore, it should account for: the specified climatic and mechanical conditions (temperature, humidity, vibration, etc.), electrical characteristics (expected impulse voltage, working voltage, temporary overvoltage, etc.) and microenvironment (pollution degree, humidity, etc.). The standard for WT converters mentions the inclusion of abnormal conditions for the testing, such as the impact of extreme ambient and environmental conditions e.g. loss of phase, excessive dust, etc.) [77].

4.5.1.2 Short circuit and overload protection

The reviewed standards all describe the requirement for converter devices to not present any hazard under short circuit or overload conditions at any point. As a result, all manufacturers are required to test for and specify the conditional short circuit current or the rated short time withstand current for every mains supply input port and any output ports connected to an input mains supply port. The exact short circuit current specifications vary slightly between LV [74] and MV [75] converter applications. Sufficient protective systems are required to detect and interrupt/limit the current flowing in any possible fault current path between conductors and/or earth. These protective systems are required unless the converter system complies with all of the normal, abnormal, and fault test conditions or has no connection to earth or has double/reinforced insulation between live parts and all parts connected to earth.

Particular specifications are made for pluggable equipment in general converter applications [74], [75], and with respect to UPSs for AC input currents, transformer protection, AC input short circuit current, protection of the energy storage device against fault- and overcurrents, and unsynchronised load transfer tests to simulate the effects of wiring connection misplacements [76].

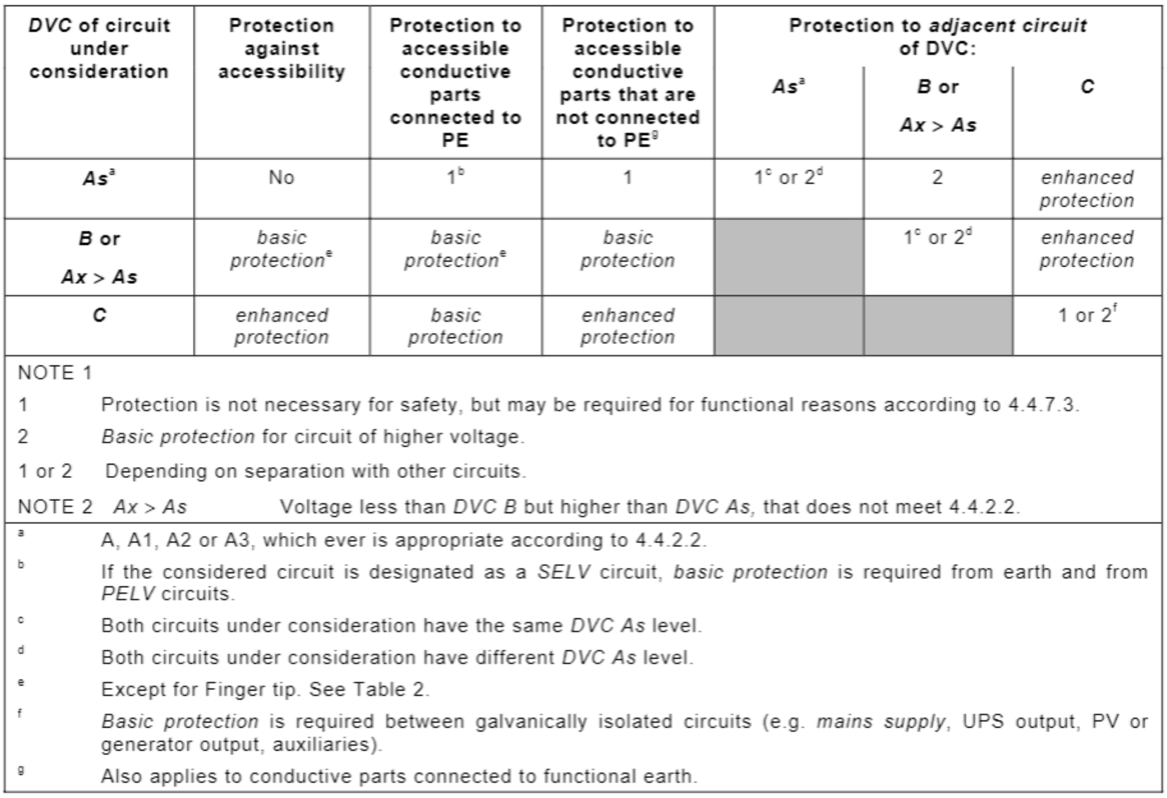
Following compliance with the relevant requirements a manufacturer is required to provide information regarding the input short circuit withstand strength, the output short circuit current ability, short circuit coordination (backup capability), protection by several devices, and the short time withstand current rating.

4.5.1.3 Protection against electric shock

The standards generally define the protection requirements against electric shock depending on the decisive voltage class and insulation standards for the given converter system. As such, the defining voltage levels and corresponding protection requirements vary depending on the converter system application. For example, the voltage level classifications vary between LV [74] and MV [75] applications, the protection procedure varies for UPS devices [76] compared to general applications, and WT converters require additional tests to assess insulation if it is not possible by visual inspection [77].

The protection should either be provided by a combination of basic protection in normal conditions and fault protection during fault conditions or using an enhanced protection system that acts across both sets of conditions. The standards describe the different procedures to provide these protection types and provide a classification table (that can vary between the different applications but an example for LV applications is shown in Table 16) that describes when each protection type is required.

Table 16. Protection requirements for circuit under consideration (for general LV converter application, specified in [74]). DVC signifies decisive voltage class.



DVC of circuit under consideration	Protection against accessibility	Protection to accessible conductive parts connected to PE	Protection to accessible conductive parts that are not connected to PE[g]	Protection to *adjacent circuit* of DVC:		
				As[a]	*B* or *Ax* > *As*	*C*
As[a]	No	1[b]	1	1[c] or 2[d]	2	*enhanced protection*
B **or** ***Ax*** **>** ***As***	*basic protection*[e]	*basic protection*[e]	*basic protection*		1[c] or 2[d]	*enhanced protection*
C	*enhanced protection*	*basic protection*	*enhanced protection*			1 or 2[f]

NOTE 1

1 Protection is not necessary for safety, but may be required for functional reasons according to 4.4.7.3.

2 *Basic protection* for circuit of higher voltage.

1 or 2 Depending on separation with other circuits.

NOTE 2 *Ax > As* Voltage less than *DVC B* but higher than *DVC As*, that does not meet 4.4.2.2.

[a] A, A1, A2 or A3, which ever is appropriate according to 4.4.2.2.

[b] If the considered circuit is designated as a *SELV* circuit, *basic protection* is required from earth and from *PELV* circuits.

[c] Both circuits under consideration have the same *DVC As* level.

[d] Both circuits under consideration have different *DVC As* level.

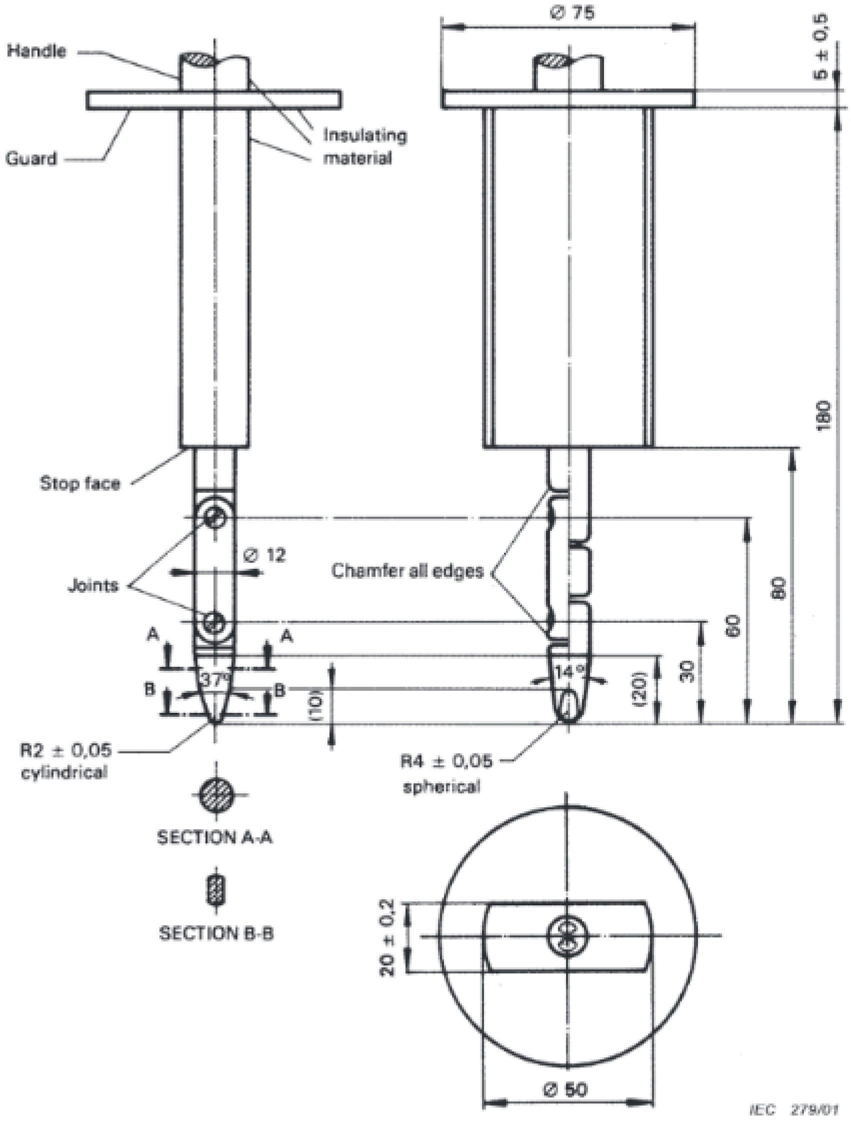
[e] Except for Finger tip. See Table 2.

[f] *Basic protection* is required between galvanically isolated circuits (e.g. *mains supply*, UPS output, PV or generator output, auxiliaries).

[g] Also applies to conductive parts connected to functional earth.

4.5.1.4 Protection against electrical energy hazards

Converter systems are required to be designed so that there is no risk of electrical energy hazard in accessible circuit areas that operators might interact with. These areas are generally defined as any location where there are two or more bare parts that a hazardous energy level exists across and are bridged by a metal object. The standards refer to the test detailed in IEC 60529 (Figure 23 in this report) [78] to determine if a bridge is possible. If possible, the design must be adapted to ensure that a hazardous energy level (defined in the standard as a voltage difference $\geq 2\,V$ when either the power exceeds 240 VA after 60 s or the energy exceeds 20 J) does not exist across the parts (by limiting the power source) or else to provide a barrier to prevent unintentional contact. The requirements are relatively consistent for all of the reviewed converter devices with minor variations to the definitions of the service access areas for UPS devices [76].



Material: metal, except where otherwise specified

Linear dimensions in millimetres

Tolerances on dimensions without specific tolerance:

on angles: 0/–10'

on linear dimensions:

up to 25 mm: 0/–0,05
over 25 mm: ±0,2

Both joints shall permit movement in the same plane and the same direction through an angle of 90° with a 0 to +10° tolerance.

Figure 23 Jointed test finger (Figure 1 in IEC 60529 [78])

4.5.1.5 Protection against fire and thermal hazards

The reviewed converter standards define the electrical circuits that are considered to be fire hazards. They include; circuits directly connected to mains, circuits exceeding the limits for limited power sources, and components with unenclosed arcing parts. The power source limits vary between LV and MV applications and depending on the use of overcurrent protections [75].

Having identified the circuits that pose fire and thermal risks, the standards require designers to use appropriate components to minimise the risk of ignition due to high temperature. An appropriate component is defined as one whose temperature for ignition is greater than the maximum working temperature under a normal/single fault condition. The standards also include the maximum operating temperatures for different materials and specify that the materials for the components and any contact in fire hazardous circuits must also comply with the flammability standards detailed in [79], [80]. The standards specify that fire enclosures should be used for all converters, unless otherwise stated. Additional requirements for components within fire enclosures (and materials for air filter assemblies) are included in the standard for WT converters [77]. The standard for UPS systems also specifies that batteries must achieve a minimum flammability class (or else be considered to pose a fire hazard risk) and provides a table of maximum temperatures for magnetic components [76].

4.5.1.6 Protection against mechanical hazards

All of the standards require converter systems to ensure that failure of any component does not release sufficient energy to lead to a hazard (such as expulsion of material into an area occupied by personnel) in normal use or a hazard that might not easily be noticed during single-fault conditions [77]. The general converter requirements on LV and MV levels specify a range of requirements for liquid cooled converters to ensure that it is unlikely to either create a dangerous concentration of the liquid in terms of the hazards mentioned throughout the standard or to drive corrosion during normal operation, storage, filling, or emptying [74], [75] while the requirements for UPS systems add that moving parts should not cause injury or else be protected against [76]. The standard for WT converters also includes requirements to minimise risk from: sharp edges, hazardous moving objects (e.g. fan blades), the protection of operators and service people, physical stability, lifting and carrying, and wall mounting [77].

4.5.1.7 Equipment with multiple sources of supply

Particularly relevant for the consideration in multiport converter design, the standards for LV and MV converters and UPS- specific devices stipulate the requirements for systems with multiple sources of supply. The standards require any device with more than one supply connection to: separate the means of connection available for different circuits and to ensure the supply connections are not interchangeable if incorrect plugging could result in a hazard. Furthermore, the standards require that the other hazards discussed throughout this report should not be introduced under normal or single fault conditions due to the multiple sources of supply.

Specifically, the standards mention that the design of converters with multiple sources of supply should consider:

- Backfeed prevention – the prevention of voltage or energy available within the converter system from being fed back to any input terminal from the other sources, either directly or by a leakage path
    - This field is discussed in more detail for UPS devices [76], which are required to prevent hazardous voltage/ energy on the input AC terminals after the interruption of the input AC power. The is specified

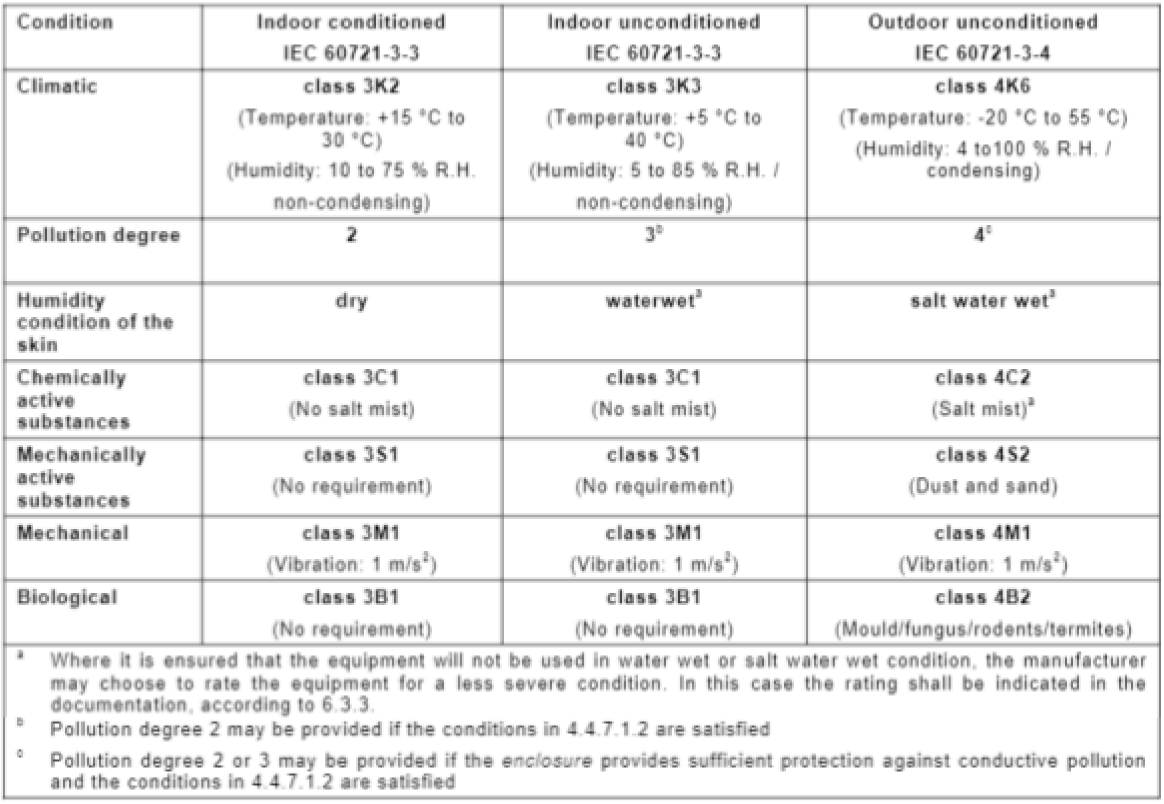
in terms of certain time- and configuration dependent requirements (e.g. ensuring that no shock hazard exists at the AC terminals 1 s after the input de-energisation for pluggable UPSs)

- Protection against unintentional islanding
- Potentially high touch current levels (while the multiple sources are connected)
- Hazards existing in one or more of the connected sources due to energy from another
- Damage to wiring due to higher currents than the wiring is designed for (driven by the additional source(s))

4.5.1.8 Protection against environmental stresses

All of the reviewed standards require manufacturers to specify the following conditions for operation, storage, and transportation to ensure that the converters can be safely maintained: coolant temperature (min/max), ambient temperature (min/max), humidity (min/max), pollution degree, vibration, UV resistance, overvoltage category (OVC), altitude for thermal consideration if rated for operation above 1000 m, and altitude for insulation coordination consideration if rated for operation above 2000 m. For MV converter applications additional design measures must also be considered for outdoor installations [75]. The UPS standard requires the specification of additional indoor environmental conditions (climatic, pollution degree, and humidity). Irrespective of the exact requirements, all of the standards require information to be provided in the form of an environmental service condition table (an example of which is pictured in Table 17).

Table 17. Environmental service conditions for LV general application converter system [74].



Condition	Indoor conditioned IEC 60721-3-3	Indoor unconditioned IEC 60721-3-3	Outdoor unconditioned IEC 60721-3-4
Climatic	class 3K2 (Temperature: +15 °C to 30 °C) (Humidity: 10 to 75 % R.H. non-condensing)	class 3K3 (Temperature: +5 °C to 40 °C) (Humidity: 5 to 85 % R.H. / non-condensing)	class 4K6 (Temperature: -20 °C to 55 °C) (Humidity: 4 to100 % R.H. / condensing)
Pollution degree	2	3[b]	4[c]
Humidity condition of the skin	dry	waterwet[a]	salt water wet[a]
Chemically active substances	class 3C1 (No salt mist)	class 3C1 (No salt mist)	class 4C2 (Salt mist)[a]
Mechanically active substances	class 3S1 (No requirement)	class 3S1 (No requirement)	class 4S2 (Dust and sand)
Mechanical	class 3M1 (Vibration: 1 m/s²)	class 3M1 (Vibration: 1 m/s²)	class 4M1 (Vibration: 1 m/s²)
Biological	class 3B1 (No requirement)	class 3B1 (No requirement)	class 4B2 (Mould/fungus/rodents/termites)

[a] Where it is ensured that the equipment will not be used in water wet or salt water wet condition, the manufacturer may choose to rate the equipment for a less severe condition. In this case the rating shall be indicated in the documentation, according to 6.3.3.

[b] Pollution degree 2 may be provided if the conditions in 4.4.7.1.2 are satisfied

[c] Pollution degree 2 or 3 may be provided if the *enclosure* provides sufficient protection against conductive pollution and the conditions in 4.4.7.1.2 are satisfied

4.5.1.9 Protection against sonic pressure hazards

The standards for LV [74] and MV general [75] and WT converter [77] applications include sections to inform how to determine if the equipment is likely to cause sonic hazard. If the equipment does exceed the allowed level, protection must be provided. Generally, testing is required and information must be provided if the maximum sound pressure level (except from alarms) exceeds 70 dBA.

4.5.1.10 Wiring and connection

All of the converter standards require wiring and connection between parts of the equipment to be protected from mechanical damage during installations. Furthermore, wiring must be provided with suitable insulation, conductors, and routing according to the electrical, mechanical, thermal, and environmental conditions of use. Any conductor that can contact another must be provided with insulation.

Information regarding the routing, colour coding, splices and connections, accessible connections, interconnections between parts of the converter systems, supply connections, and terminals must be provided for general converter applications [74], [75]. UPS systems must also be supplied with information indicating if the UPS can support copper/aluminium conductors and regarding the ability of the connecting procedure to incorporate non-detachable cords [76].

4.5.1.11 Enclosures

Additional enclosure requirements beyond any other hazard-specific features (e.g. in case of fire hazard risk) are made in the LV [74] and MV general [75] and WT [77] converter safety standards. The specifications require enclosures to be suitable for use in their intended environments, to have sufficient mechanical strength and appropriate construction so that no hazard occurs during the probable expected handling, and to be sufficiently complete to contain or deflect any parts that might become loose. The standards highlight that if the enclosure provides mechanical protection it can supplant the need for mechanical stress testing for any internal barriers. Finally, the enclosure standards detail information regarding: handles and manual controls, cast metal, sheet metal, and the stability test for enclosures.

4.5.1.12 UPS isolation and disconnection devices

The standard for UPS systems [76] requires the devices to be provided with an integral single emergency switching device (or else with terminals for its connection) to prevent further supply to the load in any mode of operation if required. The standard also includes information on the procedure to disconnect the UPS from AC or DC supplies.

4.5.1.13 Stored energy source

Specific requirements are made for the installation of batteries in the UPS converter system standard [76]. The standard defines the locations that batteries can be installed in: separate battery rooms/buildings, separate cabins/compartments, battery bays, or compartments within the UPS enclosure. Information is also provide detailing the requirements for: accessibility and maintainability, distance between cells, case insulation, electrolyte spillage, ventilation and hydrogen concentration, charging voltages, and battery circuit protection.

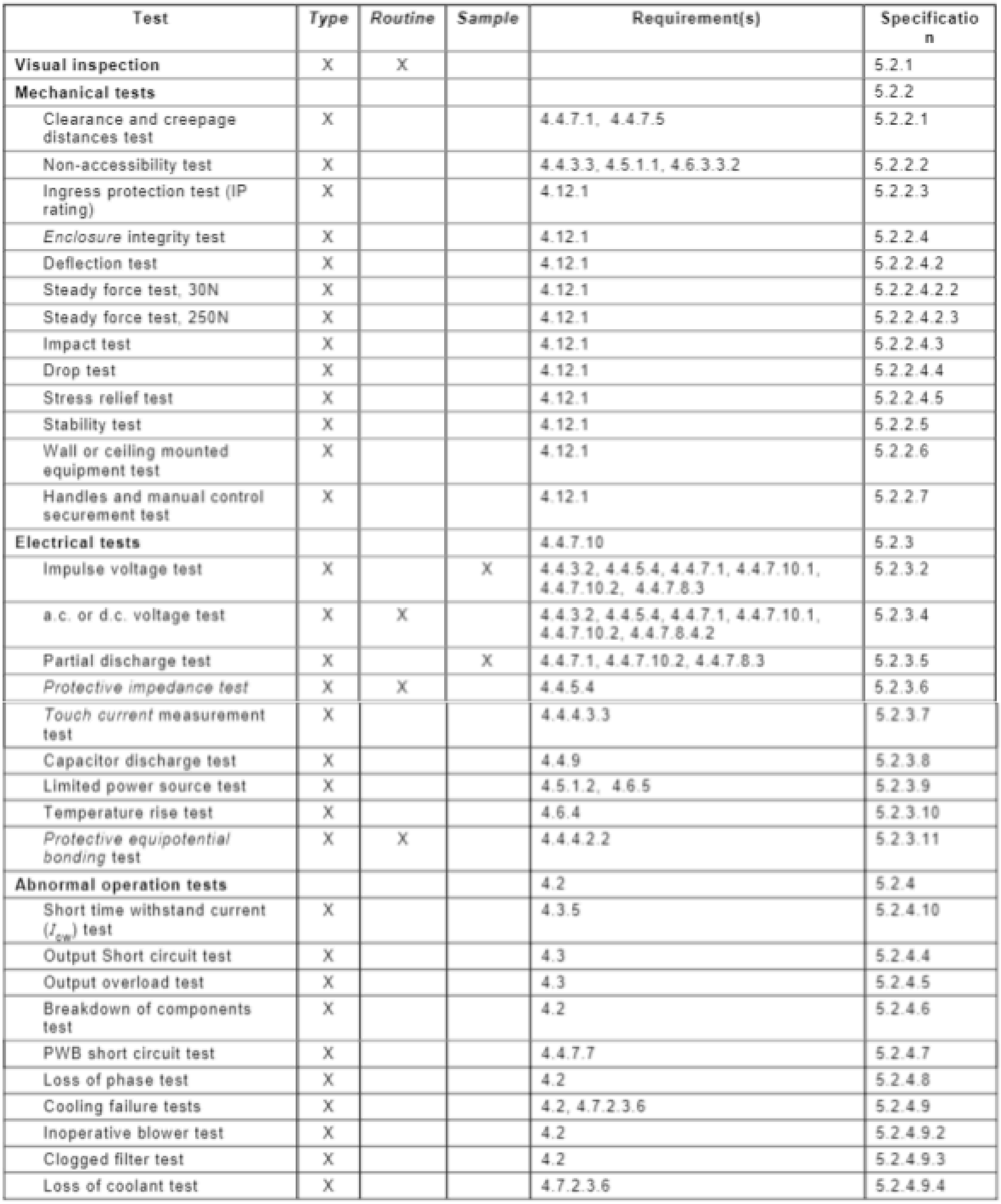
4.5.1.14 UPS connection to telecommunication lines

A final requirement for UPS converter systems [76] to protect against hazards details that terminals connecting to telecommunication lines should comply with relevant telecommunications classifications.

4.5.2 Test requirements

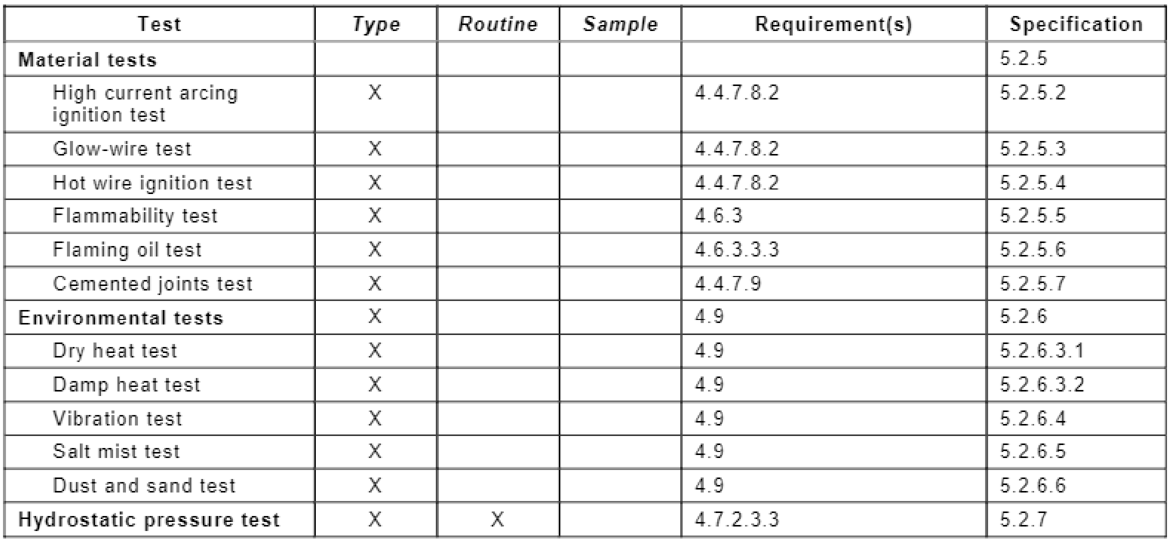
All of the reviewed safety standards include a section detailing the tests that are required to demonstrate that the converter systems meet the above-mentioned requirements. The tests are categorised as either: type, routine, or sample tests. Each standard provides a classification table, which details the type, routine, and sample testing that the electronic components, equipment, and converter systems must be subject to for each specific application (as pictured in Table 18 and Table 19 for general LV converter applications [74]). Between each application the tables vary in terms of parameterisation and content. For example, the parameterisation of some tests vary between the general converter LV [74] and MV levels [75] and additional tests are required for the specific UPS [76] and WT [77] applications.

Table 18. Test overview table for LV general application converter [74]



Test	*Type*	*Routine*	*Sample*	Requirement(s)	Specification
Visual inspection	X	X			5.2.1
Mechanical tests					5.2.2
Clearance and creepage distances test	X			4.4.7.1, 4.4.7.5	5.2.2.1
Non-accessibility test	X			4.4.3.3, 4.5.1.1, 4.6.3.3.2	5.2.2.2
Ingress protection test (IP rating)	X			4.12.1	5.2.2.3
Enclosure integrity test	X			4.12.1	5.2.2.4
Deflection test	X			4.12.1	5.2.2.4.2
Steady force test, 30N	X			4.12.1	5.2.2.4.2.2
Steady force test, 250N	X			4.12.1	5.2.2.4.2.3
Impact test	X			4.12.1	5.2.2.4.3
Drop test	X			4.12.1	5.2.2.4.4
Stress relief test	X			4.12.1	5.2.2.4.5
Stability test	X			4.12.1	5.2.2.5
Wall or ceiling mounted equipment test	X			4.12.1	5.2.2.6
Handles and manual control securement test	X			4.12.1	5.2.2.7
Electrical tests				4.4.7.10	5.2.3
Impulse voltage test	X		X	4.4.3.2, 4.4.5.4, 4.4.7.1, 4.4.7.10.1, 4.4.7.10.2, 4.4.7.8.3	5.2.3.2
a.c. or d.c. voltage test	X	X		4.4.3.2, 4.4.5.4, 4.4.7.1, 4.4.7.10.1, 4.4.7.10.2, 4.4.7.8.4.2	5.2.3.4
Partial discharge test	X		X	4.4.7.1, 4.4.7.10.2, 4.4.7.8.3	5.2.3.5
Protective impedance test	X	X		4.4.5.4	5.2.3.6
Touch current measurement test	X			4.4.4.3.3	5.2.3.7
Capacitor discharge test	X			4.4.9	5.2.3.8
Limited power source test	X			4.5.1.2, 4.6.5	5.2.3.9
Temperature rise test	X			4.6.4	5.2.3.10
Protective equipotential bonding test	X	X		4.4.4.2.2	5.2.3.11
Abnormal operation tests				4.2	5.2.4
Short time withstand current (I_{cw}) test	X			4.3.5	5.2.4.10
Output Short circuit test	X			4.3	5.2.4.4
Output overload test	X			4.3	5.2.4.5
Breakdown of components test	X			4.2	5.2.4.6
PWB short circuit test	X			4.4.7.7	5.2.4.7
Loss of phase test	X			4.2	5.2.4.8
Cooling failure tests	X			4.2, 4.7.2.3.6	5.2.4.9
Inoperative blower test	X			4.2	5.2.4.9.2
Clogged filter test	X			4.2	5.2.4.9.3
Loss of coolant test	X			4.7.2.3.6	5.2.4.9.4

Table 19. Test overview table (continued from Table 18) for LV general application converter [74]



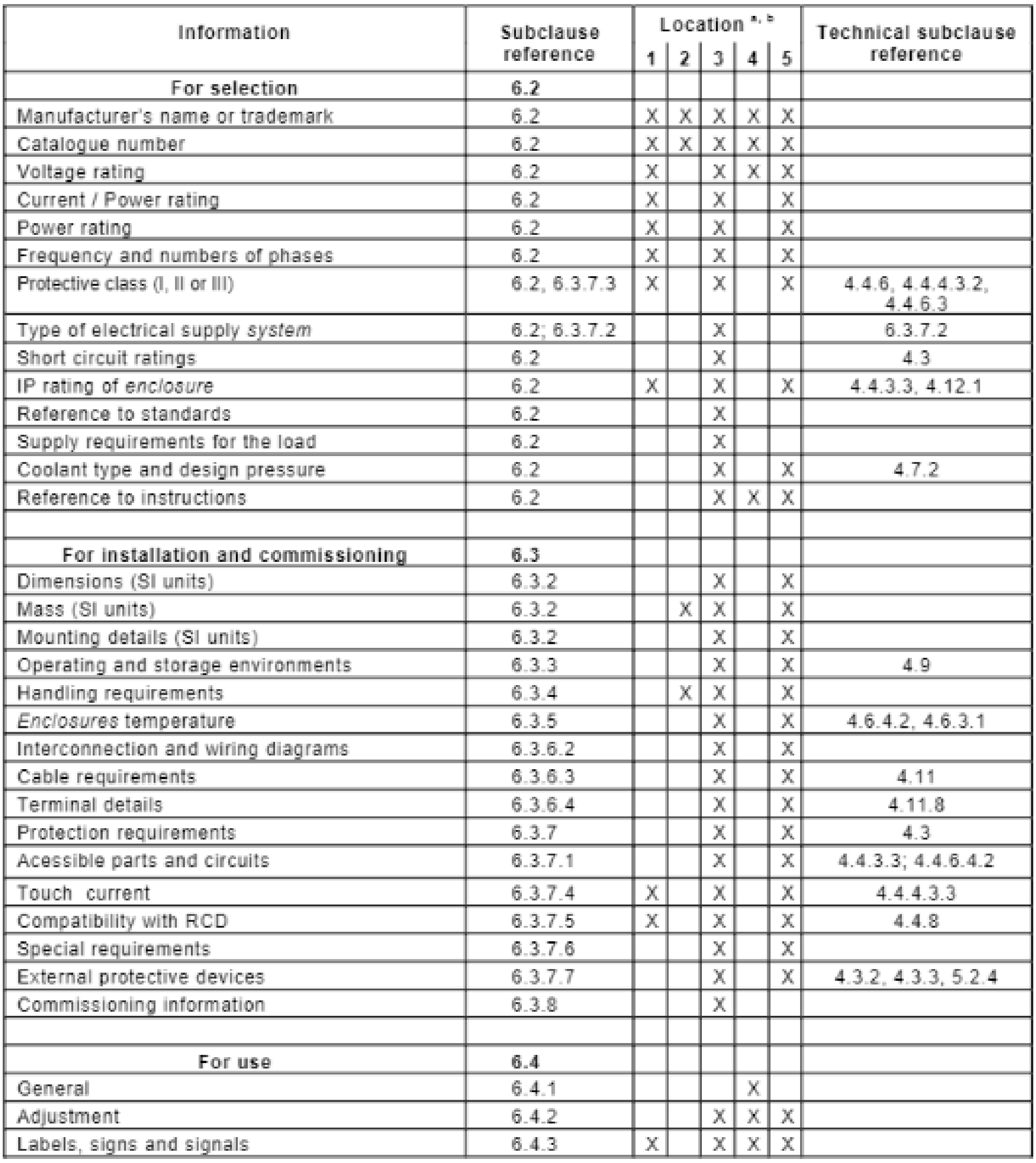
Test	*Type*	*Routine*	*Sample*	Requirement(s)	Specification
Material tests					5.2.5
High current arcing ignition test	X			4.4.7.8.2	5.2.5.2
Glow-wire test	X			4.4.7.8.2	5.2.5.3
Hot wire ignition test	X			4.4.7.8.2	5.2.5.4
Flammability test	X			4.6.3	5.2.5.5
Flaming oil test	X			4.6.3.3.3	5.2.5.6
Cemented joints test	X			4.4.7.9	5.2.5.7
Environmental tests	X			4.9	5.2.6
Dry heat test	X			4.9	5.2.6.3.1
Damp heat test	X			4.9	5.2.6.3.2
Vibration test	X			4.9	5.2.6.4
Salt mist test	X			4.9	5.2.6.5
Dust and sand test	X			4.9	5.2.6.6
Hydrostatic pressure test	X	X		4.7.2.3.3	5.2.7

The standards require that the manufacturer or test house impose appropriate environmental conditions on the devices during the tests, where the most unfavourable conditions should be imposed unless otherwise stated. Similarly, the test requirements should be determined using the worst case (most stressful) system earthing configuration allowed by the manufacturer. The system can only claim compliance once all of the relevant tests have been passed, however, there is no requirement for the tests to be performed in a set sequence or to all be performed on the same sample. Instead, appropriate test samples can be used to represent an entire range of products.

4.5.3 Information and marking requirements

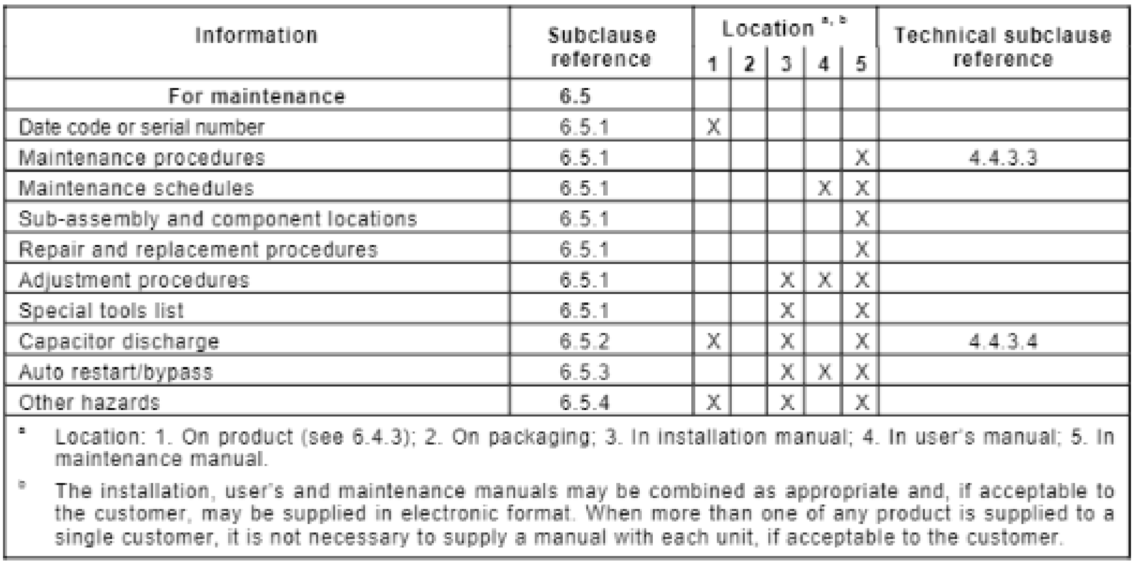
The final requirement of the reviewed standards is the provision of sufficient information and marking on devices that are available to be deployed into operation. Information is required to ensure the safe selection, installation, commissioning, operation, and maintenance of the converter systems, and is detailed in application specific tables (such as the example pictured in Table 20 and Table 21). The standards require the information to be provided in appropriate languages and to include identification references. The information requirements vary slightly between the specific applications, including a different marking for installation procedure for the UPS converter systems [76] compared to the general and WT application converter systems.

Table 20. Information requirements table for LV general application converters [74]



Information	Subclause reference	Location[a, b]					Technical subclause reference
		1	2	3	4	5	
For selection	**6.2**						
Manufacturer's name or trademark	6.2	X	X	X	X	X	
Catalogue number	6.2	X	X	X	X	X	
Voltage rating	6.2	X		X	X	X	
Current / Power rating	6.2	X		X		X	
Power rating	6.2	X		X		X	
Frequency and numbers of phases	6.2	X		X		X	
Protective class (I, II or III)	6.2, 6.3.7.3	X		X		X	4.4.6, 4.4.4.3.2, 4.4.6.3
Type of electrical supply *system*	6.2; 6.3.7.2			X			6.3.7.2
Short circuit ratings	6.2			X			4.3
IP rating of *enclosure*	6.2	X		X		X	4.4.3.3, 4.12.1
Reference to standards	6.2			X			
Supply requirements for the load	6.2			X			
Coolant type and design pressure	6.2			X		X	4.7.2
Reference to instructions	6.2			X	X	X	
For installation and commissioning	**6.3**						
Dimensions (SI units)	6.3.2			X		X	
Mass (SI units)	6.3.2		X	X		X	
Mounting details (SI units)	6.3.2			X		X	
Operating and storage environments	6.3.3			X		X	4.9
Handling requirements	6.3.4		X	X		X	
Enclosures temperature	6.3.5			X		X	4.6.4.2, 4.6.3.1
Interconnection and wiring diagrams	6.3.6.2			X		X	
Cable requirements	6.3.6.3			X		X	4.11
Terminal details	6.3.6.4			X		X	4.11.8
Protection requirements	6.3.7			X		X	4.3
Acessible parts and circuits	6.3.7.1			X		X	4.4.3.3; 4.4.6.4.2
Touch current	6.3.7.4	X		X		X	4.4.4.3.3
Compatibility with RCD	6.3.7.5	X		X		X	4.4.8
Special requirements	6.3.7.6			X		X	
External protective devices	6.3.7.7			X		X	4.3.2, 4.3.3, 5.2.4
Commissioning information	6.3.8			X			
For use	**6.4**						
General	6.4.1				X		
Adjustment	6.4.2			X	X	X	
Labels, signs and signals	6.4.3	X		X	X	X	

Table 21. Information requirements table (continued from Table 20) for LV general application converters [74]



Information	Subclause reference	Location [a, b]					Technical subclause reference
		1	2	3	4	5	
For maintenance	**6.5**						
Date code or serial number	6.5.1	X					
Maintenance procedures	6.5.1					X	4.4.3.3
Maintenance schedules	6.5.1				X	X	
Sub-assembly and component locations	6.5.1					X	
Repair and replacement procedures	6.5.1					X	
Adjustment procedures	6.5.1			X	X	X	
Special tools list	6.5.1			X		X	
Capacitor discharge	6.5.2	X		X		X	4.4.3.4
Auto restart/bypass	6.5.3			X	X	X	
Other hazards	6.5.4	X		X		X	

[a] Location: 1. On product (see 6.4.3); 2. On packaging; 3. In installation manual; 4. In user's manual; 5. In maintenance manual.

[b] The installation, user's and maintenance manuals may be combined as appropriate and, if acceptable to the customer, may be supplied in electronic format. When more than one of any product is supplied to a single customer, it is not necessary to supply a manual with each unit, if acceptable to the customer.

4.6 Discussion

The review shows that the existing requirements for converters are generally established for a single energy source/sink and a single high-level objective for its interconnection with a single network. This allows the relatively straightforward establishment of a minimum acceptable capability. Even the requirements for prosuming devices, such as interconnectors, energy storage, or EV chargers, appear to be moulded to fit into a similar frame of reference where a minimum capability to support/comply with the network is simply adapted according to the technology’s energy characteristics.

In contrast, MPCs will have three or more ports that may have time-varying objectives and may interface to multiple networks. These features make the definition of a minimum capability difficult. It is expected that similar requirements to those observed above for DERs will continue to be asked of the individual ports of a MPC that interface to a network. However, these specific requirements will fail to account for the energy flexibility of MPCs and will be difficult to define according to the characteristics of potentially multiple energy sources behind the MPC. Therefore, it may also be beneficial or necessary to define connection requirements for the overall MPC (similar to the proposal of the different grid code requirements for DC collection pool versus AC-connecting converters for MVDC networks [21]).

MPC requirements could be specified as follows. Each network-connecting can be subject to Individual Port Requirements, similar to existing DERs, to ensure its compliance with safety requirements and to at least maintain the grid’s stable operation. Then additional Overall MPC Requirements could be specified to ensure the device’s overall operation for high energy density functions that utilise the energy flexibility of the multiple ports. Further analysis will need to be made to decide if these requirements are specified according to the minimum or maximum energy source capability (or somewhere in between), which will have a knock-on effect on the strain on the converter and the likelihood of its compliance with the requirements. Equally, instead of specifying these high energy density functions as requirements, they may feature as grid services that are defined in a market arrangement, in which case more strenuous provision can be better compensated. The proposed organisation of the Individual Port Requirements versus Overall MPC Requirements is indicated in Figure 24*.*

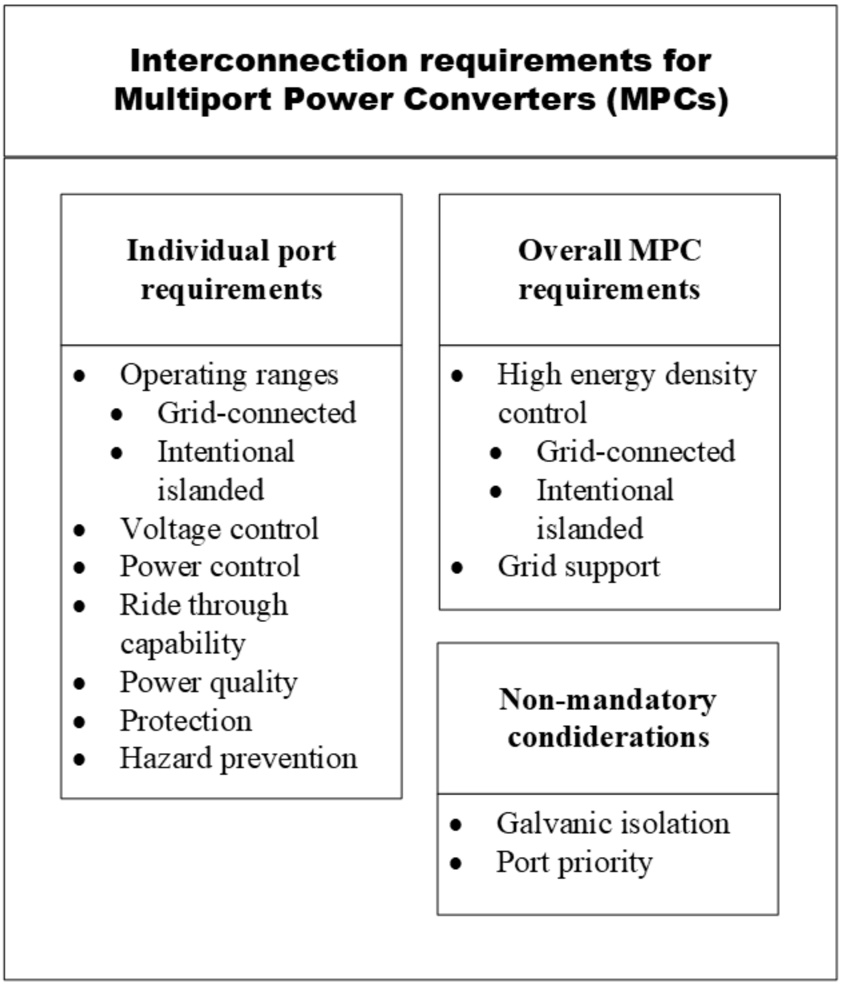


Figure 24 Proposed structure of grid code and safety standard requirements for MPCs in terms of Individual Port and Overall MPC requirements.

As well as the overall structure of requirements for MPCs, additional work needs to be carried out for the specification of some individual requirements. One objective of MPCs is to use their combined energy capacity to provide advanced support the grid. Although specifications are being developed for this grid support functionality ([25], [30], [81], [82]) it is still in its infancy and needs to be made more transparent e.g. [66]. MPCs are expected to operate in both grid-tied and islanded conditions, which will require further assessment and specification of the appropriate converter operational features in both conditions. Prosuming devices also need to be better specified to allow their accurate quantification and standardisation and therefore the maximisation of their benefits for the grid.

Finally, the requirement of galvanic isolation was identified as a field of particular interest to provide direction on potential MPC design. The only grid code that was identified to explicitly require isolation was the Ecuadorian requirements for PV

<100 kW [40]. However, isolation appears in technical and safety standards either as a conditional solution (to achieve a requirement under specific circumstances) or as an option to improve the converter's performance. For example, an isolating transformer is required as a conditional solution to interface limited power sources to an AC mains supply in the Safety Standards for LV [74] and MV general converter applications [75] and for UPS converters [76]. Alternatively, galvanic isolation is described to improve converter's performance in the following settings: to minimise the hazards under normal or single fault conditions for equipment with multiple sources of supply [74]–[76], to minimise the impact that earth faults have on protection devices, to prevent long term damage due to conducted disturbances, and to prevent the propagation of hardware failure between input-output ports [83].

5 Key Performance Indicators

The following section of the report introduces Key Performance Indicators (KPIs) selected to provide MPC technologies assessment for given case studies. KPIs are generated to highlight benefits resulting from use of MPC over other alternative solutions currently used to integrate networks and devices, considering some scenarios from Section 3.

KPIs are divided between two groups. First, includes indicators defining overall improvements in operation of the power distribution system after installation of MPC. Second, delivers comparison between MPC configuration and alternative methods to integrate appliances using more conventional approaches to achieve similar functionalities.

Further assessment of MPC topologies is covered in Section 6 where range of selected MPC topologies is compared considering Key Features specific for each of them. Section 6 also reveals ranking methodology proposed to match specific topology for given study case. Assessment takes into account number of ports, bidirectional power flow capability, isolation and more.

5.1 Network KPIs

The first group of KPIs was introduced to highlight benefits resulting from introduction of MPC within distribution networks. This can be accomplished by performing a comparison of four different network arrangements summarised in Figure 25 below.

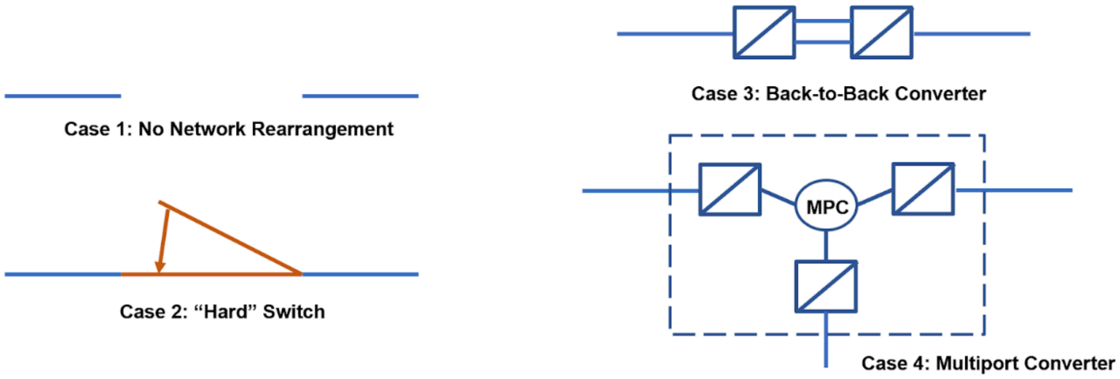


Figure 25 Four Network Arrangements for Networks KPIs.

Network KPIs are expected to highlight performance of MPC under configurations chosen by Estabanell. Available data characterising LV and MV networks give sufficient information to model selected scenarios and to assess KPIs for Enhanced Soft Open Points with Renewable Energy Sources. Fundamental outcomes resulting from load flow analysis are expected to provide information regarding system efficiency, power network availability and other aspects summarised in sections below. The flowchart presenting methodology used to conduct KPIs network analysis is presented in Figure 26.

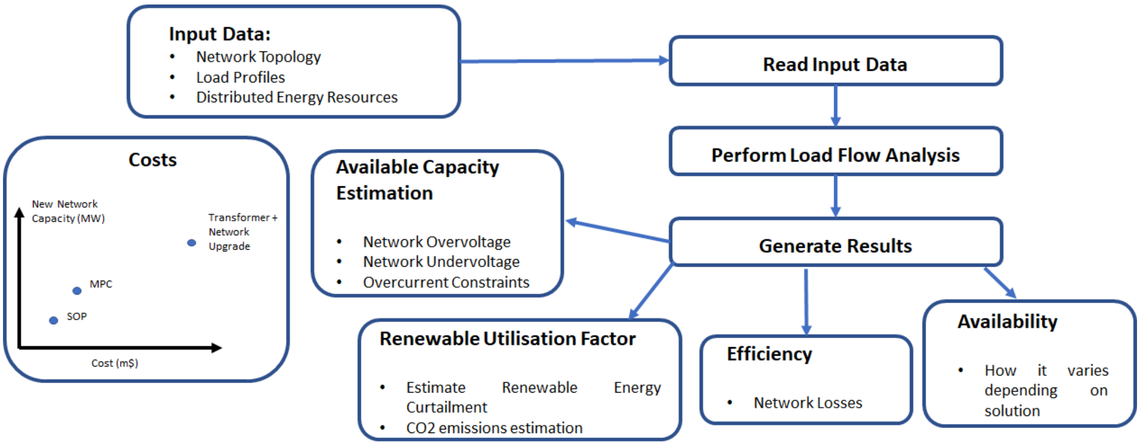


Figure 26 Proposed Methodology for Network KPIs.

Based on the flowchart presented in Figure 26, identification of Network KPIs is based on input data providing Network Topologies, Load Profiles and information regarding Distributed Energy Resources. Once network models are established, load flow examination is required to generate results allowing further analysis of benefits and challenges associated with each topology. The final results are expected to give understanding between network configurations based on KPIs listed below:

Available Capacity Estimation – KPI used to define network constraints. It aims to provide information on available power capacity for DER integration before reaching overvoltage and overcurrent threshold levels. Other analysis should also give understanding on available capacity for connection of new loads before reaching under voltage limits. Furthermore, studies are required to highlight maximum power transfers capacities under each scenario. This is dictated by the network cable design.

Proposed equation to estimate Available Voltage Capacity within LV/MV networks is summarised by the formula below:

$$\text{AVC}= \frac{Network\ Operation\ Time\ within\ Voltage\ Limits}{Total\ Operating\ Time}\ x\ 100\% \qquad (1)$$

Similarly, available current capacity could be estimated using equation (2):

$$\text{ACC} = \frac{Network\ Operation\ Time\ within\ Current\ Limits}{Total\ Operating\ Time}\ x\ 100\% \qquad (2)$$

Renewable Utilisation Factor – KPI used to understand how well renewable generation can be adapted within selected networks before and after rearrangements. Currently, wind or solar generation sources are frequently required to reduce their production due to technical constraints on the distribution network [84]. Introduction of MPC could mitigate some of these issues and ultimately increase utilisation of low carbon power generation sources.

The outcome of the Renewable Utilisation Factor KPI is expected to be a parameter giving understanding of what amount of renewable energy can be exported to power system out of estimated full renewable production under no network constraints. The formula to establish such estimation is given below:

$$\text{RUF} = \frac{Energy\ Exported\ by\ Local\ Renewables}{Total\ Energy\ Production\ without\ Network\ Constraints}\ x\ 100\% \qquad (4)$$

Efficiency – Load flow analysis also aims to provide important parameters to identify overall distribution network losses under each investigated scenario. Introduction of MPC can offer appropriate voltage regulation capabilities and optimal power management allowing minimisation of losses in the system. The main outcomes of Efficiency KPI are expected to give understanding of the proportion of annual energy consumed by the users over the whole amount of energy used, including losses. The formula proposed for this analysis is presented below:

$$\text{Efficiency} = \frac{Annual\ Energy\ Required\ by\ Local\ Demand}{Annual\ Energy\ Distribution\ within\ Investigated\ Networks}\ x\ 100\% \qquad (5)$$

Network Costs - The outcome of this KPI is expected to be determined depending on the level of details revealed under Converter Cost KPI (See Section 5.2). Successful converter cost approximation could support Network Costs estimation for all four arrangements considering payback period for each of them. Alternatively, for cases where cost estimation of MPC is not provided, Network Costs KPI could fully focus on revenues gathered by the renewable generation company operating under each of given network arrangements. As such, introduction of MPC could improve balance of loads between network feeders resulting in higher renewable energy contribution after implementation of MPC. As a result, lower amounts of electricity would be curtailed, boosting revenues for a company operating DERs.

Availability – This KPI is considered as optional for the network analysis. The main outcomes are expected to give understanding of differences between power supply being available to meet load demand. The KPI could provide outcomes mainly for the Interconnected Communities scenarios where off-grid microgrids frequently experience challenges associated with maintaining balance between electricity supply and demand (see Section 3.3). Interconnections between off-grid microgrids using iPLUG MPC could mitigate some problems and increase time when customers have reliable access to electricity. Proposed formula for availability estimation is provided below.

$$\text{Availability} = \frac{Total\ number\ of\ hours\ when\ Electricity\ is\ Available}{8760\ hours}\text{x } 100\% \qquad (6)$$

5.2 Converter KPIs

Converter KPIs were defined to highlight benefits of MPC topologies over conventional solutions enabling integration of multiple devices using different system topologies. Example summarizing fundamental differences between two converter topologies for study case involving two MV distribution feeders and distributed solar generation capacity is presented in Figure 27.

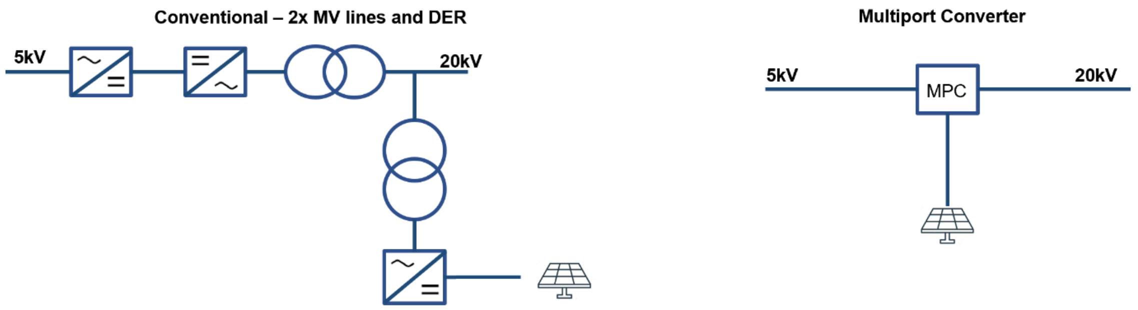


Figure 27 Integration of two MV Lines and PV Array using Conventional Approach and MPC.

Each power conversion method for integration of two distribution network feeders with renewable electricity (highlighted in Figure 27) may present some opportunities and challenges. In order to identify them, a set of Converter KPIs is proposed. The initial selection of KPIs was based on previous analysis conducted at the Chalmers University of Technology (CUT) where topology of MPC is compared to traditional methods for integration of smart devices at the household level. KPIs selected by CUT are therefore used for preliminary comparison between power converters and further expanded by the iPLUG consortium. The final list of proposed Converter KPIs is presented below.

Table 22 Comparison between Number of Modules required to Convert Power Under Each of Investigated Scenarios.

Converter	Grid Filter	Diodes	Transistors with anti-parallel diodes	dc-filters
Garage Storage	1	0	6	1
Solar Panels	1	1	7	2
DC Charger	0 (1)	3x9 (4)	3 x 5 (10)	3 x 2 (2)
TOTAL	**2 (3)**	**28 (5)**	**28 (23)**	**9 (5)**
4-port Converter	1	0	4x4+6	4
TOTAL	**1**	**0**	**22**	**4**

Power Converters Design - KPI proposed to present a comparison between the number of modules required to achieve desired functionality. The analysis considers switches, diodes, filters and other elements required to convert power under investigated topologies. Example used by CUT presenting assessment between integration of household appliances using MPC and conventional method is summarised in Table 22. The studies prove that the overall number of modules required to integrate listed appliances is lower than needed while using conventional methods. As a result, installation of MPC could reduce the total cost of adapting considered devices on the household level.

Efficiency – Indicator which can be quantified either by performing analytical studies of power converters or by simulating their operation in selected SPICE software [85]. Studies are expected to highlight efficiencies based on several cases, each considering different loading on the MPC and each individual port. Alternative methods for efficiency assessment within MPC could be based on a simplified load model where performance of the MPC is defined according to available daily profile data. The final method for efficiency assessment has not been decided yet. This will require further understanding of case studies scenarios, converter topology as well as input data provided by project partners defining scenarios.

Footprint – depending on MPC applications, size of the MPC can be a considerable aspect while comparing various approaches to integrate distribution networks, renewable electricity generation and energy storage. As a result, this KPI aims to compare the volume and mass for each configuration investigated. Some methodologies proposed for footprint estimation were identified while conducting literature review and can be used as reference for the MPC size estimation [86]–[88]. They introduce methodologies for estimating MFPT (Medium Frequency Power Transformer) volume considering efficiency and heat dissipation. Further analysis can consider footprint estimation of some other components within MPC including inductors and capacitors.

Control and Signals – Comparison used to identify number of signals to be measured in order to successfully introduce power transfer capabilities. KPI should also identify the number of parameters required to control.

Converter Costs – KPI expected to give cost comparison between converter configurations based on the number of modules required to obtain given system topology. Some methodologies to identify power converter costs consider analysis of individual components and translating them to corresponding currency [89], [90]. Components that require cost estimation include filters, diodes and transistors for each configuration. Converter cost KPI analysis will also be expanded by comparing impact of overall size of the magnetic component as well as heat sink - the largest expected elements of the MPC. It is yet unknown whether the numerical values estimating converter costs can be provided from the analysis, however reduction in number of modules and converter footprint could give some estimation of cost savings resulting from implementation of MPC over other conventional methods for integration of distribution networks with renewables and/or energy storage devices.

5.3 KPI Conclusion

Chapter 5 reveals methodology proposed to assess benefits of MPC over conventional methods used to integrate ports, devices and appliances considering case studies highlighted in Section 3.

Proposed KPIs are expected to provide numerical results as outcomes from the following analysis performed under work packages 1, 2 and 3. Methodologies used to assess KPIs were selected considering the main objectives of the iPLUG project as well as data availability provided by the consortium partners.

6 Multiport power converter topology literature review

6.1 Introduction

This section has been developed to offer a foundational literature review of multiport power converter (MPC) topologies. The review provides an overview of the existing MPC topologies to feed into the later design and optimisation of MPCs for the iPLUG project and its relevant applications. The literature review will discuss the benefits and constraints of as full a range of topologies as possible to ensure that the later design does not become pre-emptively focussed on any given solution.

A methodology for the identification of suitable topologies for several applications is described in Section 6.2, alongside a description of the key features that will be mentioned in the review. It includes the qualification of topologies depending on their critical requirements, the weighting of a suite of features that describe their desirable capabilities for specific applications, and the scoring of the topologies in terms of these features. The specific case studies are derived from the applications in Section 3, but are defined in more detail in Section 6.2.1. As well as identifying topologies that are currently suited to provide the desired functionality, the scoring method is useful to highlight the important fields that MPC design should meet and the areas that topologies can be improved.

The literature review is carried out and presented in Section 6.3. The results of the feature weighting and scoring are presented in Section 6.4. A final discussion of the findings of the literature review and the weighting and scoring methodology is presented in Section 6.5.

6.2 Pugh Matrix weighting and scoring methodology

An adapted Pugh Matrix method [7], [91], [92] is used to identify suitable MPC topologies for different applications. The method accounts for the variable importance of the key features of MPC operation for the different applications and can also be useful for highlighting areas that future research should focus to improve the MPC technology readiness level. The method consists of four stages, each of which is repeated for every scenario/application of interest:

- Definition of the scenario and its critical requirements
- Qualification of topologies for the scenario according to the critical requirements
- Weighting of desirable features for the scenario
- Scoring of topologies for the scenario in terms of the desirable features

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. Table 23 depicts the four scenarios and their critical features that will be used to qualify topologies. Each scenario is derived from the applications that MPCs are identified to be suitable for in Section 3.

Table 23 iPLUG scenario specifications and qualifying features. * Indicates the assumption that the EV port only charges and does not provide vehicle to grid services.

Scenario		Application	Qualifying (port) features			
			Total ports	**Bi-directional ports**	**AC ports**	**DC ports**
1	Enhanced SOP	2x20 kV feeders, 1x100 kW PV	3	2	2	1
2	Residential building	1xLV feeder, 1xLV PV, 1xLV ESS, 1xLV EV charger	4	2*	1	3
3	Facility building	1xLV PV, 1xLV BESS, 1xLV Diesel gen, 1xLV AC load, 1xLV feeder	5	2	3	2
4	Interconnected community	1xLV PV, 1xLV ESS, 1xLV feeder, + future MV grid expansion	3+1	2+1	1+1	2

The topologies' critical features are compared with the requirements in Table 23 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 to meet the requirements. This use of an inverter is stated as a common solution for DC-DC MPCs [1] 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 4 per additional inverter to meet the scenario specifications.

The weighting stage then defines the importance of the remaining 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 very important for the given application. Although the desirable features with a weight of 3 are very important they are not deemed to be necessary for the given application. The features, their weights, and the justification of these weights for different applications are described in Section 6.2.1.

The desirable features of each topology identified throughout the literature review are assigned a normalised score between 0 and 1 (also described in full detail in Section 6.2.1). These scores are then multiplied with their corresponding feature weights. The sum of these products describes a topology's suitability for any given application. The contribution of each feature towards a topology's overall score can also indicate areas that different topologies are strong/weak in and where research efforts should be focussed.

6.2.1 Key features and weighting

Table 24 Weighting of key features for iPLUG scenarios

Feature		Weight			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Power		0	0	0	0
Voltage	Peak port	0	0	0	0
	Maximum gain	3	1	1	2
Isolation		3	2	1	2
Port/cell interconnection		0	0	0	0
Voltage decoupling		2	2	2	2
Resonance		1	1	1	1
Modularity		1	1	1	3
Scalability		2	0	0	1
Number of switches		3	3	3	3

The weights applied to each feature in the adapted Pugh Matrix Method is pictured for each scenario in Table 24. The weights are justified in this subsection.

- Examples of power and peak port voltage – although experimental examples of power and voltage are recorded throughout the review of MPC topologies and pictured in Table 31, both features represent example scales that are adopted for prototypes. The suitability of a topology to support high power or voltage may instead be better represented by other features such as voltage gain, isolation, or scalability. As a result, both features are assigned a weight of zero for all of the scenarios.

- Maximum voltage gain between ports – voltage gain (which is defined here as the maximum difference in port voltages in a MPC) is important to support the step-up of different voltage level devices [1]. This feature is beneficial for all of the scenarios described in Table 23. However, voltage gain becomes increasingly important as the scale of the step-up increases.

Therefore, voltage gain is assigned a weight of: 1 for Scenarios 2 and 3, which only interface LV devices, 2 for Scenario 4, which may be required to step its original port voltages up to MV levels during grid expansion, and 3 for Scenario 1, which will require the matching of LV RESs to the MV feeders.

- Isolation – as discussed in Sections 2.1 and 4, galvanic isolation allows the safe interconnection of different devices by offering an electrical disconnection between different ports and their voltages. Therefore, isolation is assigned an increasing weight as a scenario is expected to interface increasingly mismatched voltage levels. An outlier to this trend is Scenario 2, which is assigned a higher isolation weight than Scenario 3, due to its requirement to interface an EV charger that normally requires isolation [93].
- Port/cell interconnection – Cell interconnection is a feature that stems from the interconnection of submodules in multilevel converter configurations and could signify a topology's suitability for high voltage applications (by serially stacking cells/submodules) [94]. However, its definition appears to become confused in some cases. For example, cascaded H-bridge MPCs are referred to as being connected in series when the voltages established by each submodule sum to give a larger output voltage, whereas, a switched capacitor topology is referred to as being series connected when the voltages established by its submodules share the same output voltage (and is referred to as parallel when the submodule voltages sum to give the output voltage) [2]. Moreover, it is unclear if one port interconnection clearly outperforms another and can be difficult to define when ports operate bidirectionally or in single-level configurations. Therefore, although discussed in Section 6.3, port/cell interconnection is assigned a weight of zero for all of the scenarios.
- 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 [95]. Although Scenario 1 doesn't interface a RES with an ESS, voltage decoupling is still deemed to be reasonably important due to the application's requirement for a fixed coupling voltage to maintain stable power transfer between the AC feeders [96]. Therefore, voltage decoupling is assigned a weight of 2 for all of the scenarios.
- 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 [97]. The hard-switching operation can also drive current fluctuations that impact the lifetime of ESSs [95], [98]. 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) [99] but can also be associated with complex control circuits and higher device stress [97].

- Modularity – modularity describes the ability of a MPC to increase or decrease its number of ports as its needs vary with increased ease and reduced cost compared to non-modular devices [100]. Modularity is desirable but not highly important for all of the scenarios (which are assigned weights of 1) other than Scenario 4. Modularity is assigned a weight of 3 for Scenario 4, which expects the number of ports to vary during either the MV grid expansion or the development of the community's needs.
- Scalability – scalability indicates the ability of a topology to be extended to higher voltage/current (and therefore power) levels by rearranging devices, submodules, or even branches [101]. Again, this feature stems from the different connection approaches of multilevel converters, however, now refers to a more explicitly beneficial ability to increase the power level. Therefore, it is assigned non-zero weights, unlike the less globally definable or beneficial port/cell interconnection feature. Scalability is assigned a weight of: 2 for the likely higher voltage and power Scenario 1 application, 1 for Scenario 4, which may be extended to higher voltage levels, and a weight of 0 for the low voltage Scenarios 2 and 3.
- Number of switches and number of passive devices – the number of switches and number of passive devices both represent proxies for the cost and size of a converter. It is desirable to achieve a lower number of both switches and passive devices to reduces the cost and losses and to increase the power density of a MPC [1]–[3]. Both features are highly important for the feasibility of a topology so are assigned a weight of 3 for all of the scenarios.

6.3 Review of topologies

The following sections detail existing MPC topologies and their key characteristics. Table 31 provides an overview of all of the topologies and their features arranged according to their isolation class. The isolation class is developed from the definition of MPCs in Section 3, where the isolated family includes C1 – multi-winding single transformer and C2 – single winding multi-transformer classes, the non-isolated family includes C3 – DC capable and C4 – AC and DC capable classes, and the partially isolated family includes C5 – non-integrated and C6 – integrated classes.

6.3.1 Non-isolated

6.3.1.1 DC capable

DC capable non-isolated MPCs don't include any inherent AC ports. Generally, these topologies are suggested to be implemented with an additional inverter or some other AC output power converter to interface with AC networks and loads. As described in [1], DC capable non-isolated MPCs can be categorised as one of the following configurations: combined input/output ports, reconfigurable ports, or magnetically/capacitively coupled ports.

Combined input/output port non-isolated MPCs combine various simple (boost or buck) or complex (half or full bridge) converter cells to interface 3 or more ports. Their low device count enables them to achieve high efficiencies. The simple configurations can constrain some topologies to single unidirectional power flow modes or else to enforce the deactivation of some ports at any given time. This low flexibility can be sufficient for the simple integration of PV and ESS resources.

[4] proposes an example of a combined input/output port MPC that combines a boost with a bidirectional buck converter to integrate a PV and ESS with a DC load (pictured in Figure 28). The boost supports unidirectional power flow from the PV, while the buck supports bidirectional flow in or out of the ESS to support its charging and discharging. The proposal claims high efficiency (>96 %) and low electromagnetic noise.

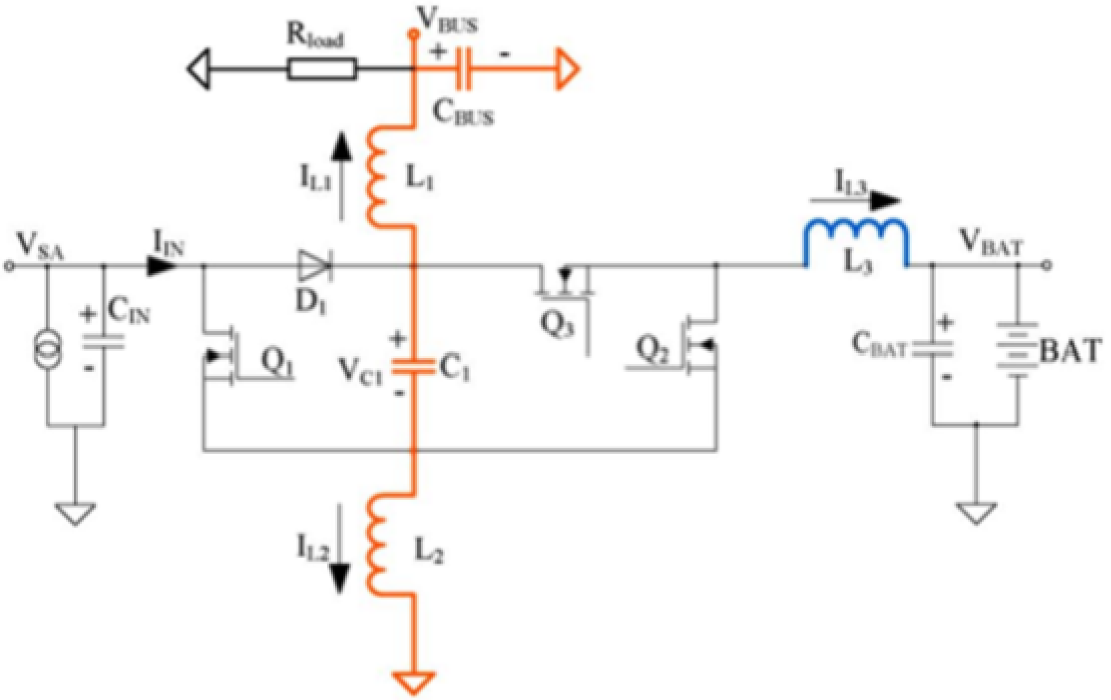


Figure 28 Cascaded boost converter as proposed in [4]

Another family of DC capable non-isolated MPCs also combine different (often simple) converter cells, similar to the combined input/output port MPCs, however, they also use either magnetic or capacitive couplings that can enhance the voltage boost between the ports. This large voltage boost can be particularly useful for the integration of RESs, ESSs, and power systems, all of which can possess different voltage levels. However, to achieve the large voltage boost, magnetically/ capacitively coupled MPCs can be complex and less efficient (due to an increased number of devices) compared to other non-isolated topologies.

[114] proposes a MPC that links two cascaded boost converters using a coupling inductor to achieve sufficient voltage gain to boost from a PV & ESS resource onto a higher voltage SST-enabled DC microgrid (pictured in Figure 29). The use of the coupling inductor allows the boost converter to avoid the extreme duty cycles that would otherwise be required. The converter is capable of utilising several operating modes, however, only the ESS port is capable of varying the direction of its power flow. The additional use of an active clamp introduces resonance to the converter that supports soft-switching and therefore reduces its switching losses.

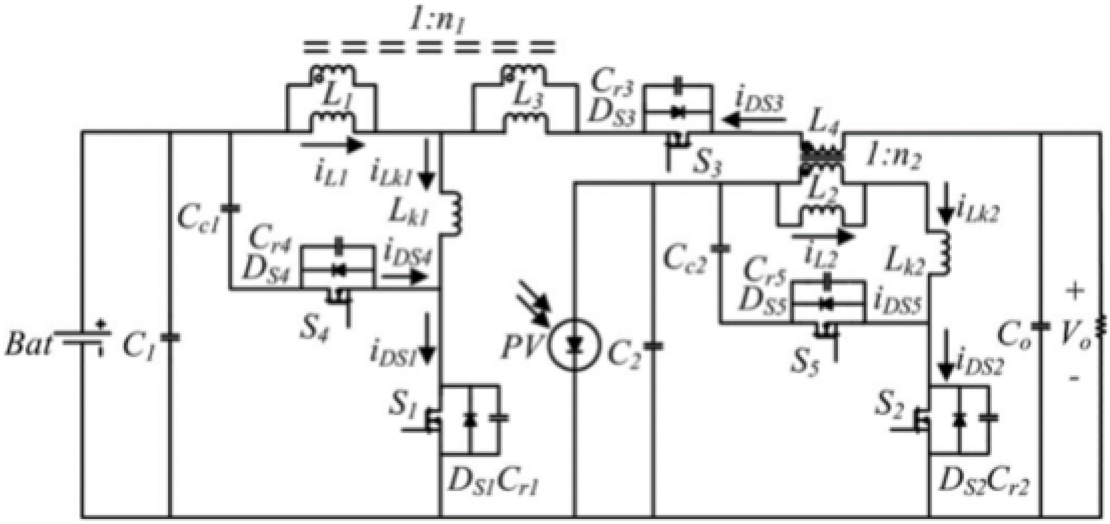


Figure 29 Magnetically coupled three-port DC-DC MPC as proposed in [114]

6.3.1.2 AC and DC capable

AC/DC capable non-isolated MPCs generally possess similar features as DC capable non-isolated MPCs (often achieving good efficiencies due to their relatively simple configurations and lack of a transformer core), however, offer improved power density when integrating to AC systems due to the integrated AC-output converter stage. Such applications are common in residential and nanogrid cases, where AC and DC loads are regularly delivered by DC sources such as Solar PV. The bidirectional flexibility of AC/DC capable non-isolated MPCs can vary depending on the topology.

Derived converters represent one family of AC/DC capable non-isolated MPCs that have been developed by hybridising conventional converter configurations. These topologies have generally been developed to improve the efficiency of the residential and nanogrid integration application described above, where DC and AC loads (e.g. ESS or EV charger plus AC grid) are expected to be served simultaneously. The efficiency is improved by reducing the number of switches and losses compared to a conventional back-to-back configuration. Many derived converters only aim to integrate three ports but can offer simple control circuits, compact design, and therefore reduced cost for this specific application.

Specific configurations of derived converters possess different characteristics. The boost derived hybrid converter, proposed in [116] replaces the switch of a conventional boost converter with a full-bridge converter to enable the provision of DC and AC loads simultaneously from a single DC source (pictured in Figure 30). The DC load is delivered using the DC output, while the AC load can be integrated across the inductor of the full-bridge converter. The configuration is capable of feeding both the AC and DC loads during all of the power modes using either the injection from the DC source, the full-bridge’s circulating current, or the discharge of the DC capacitor. Single- and three-phase configurations of the boost derived hybrid converters exist, as well as multilevel configurations that interlace multiple individual hybrid converters, sources, and loads [124]. An alternative derived converter is the quadratic boost derived hybrid converter, which replaces the switch of a quasi-boost converter with a full-bridge converter and uses a similar operating principle as the boost derived hybrid converter but achieves a greater voltage gain by utilising an additional 2 diodes and 1 capacitor [125], as well as reduced AC voltage ripple [126].

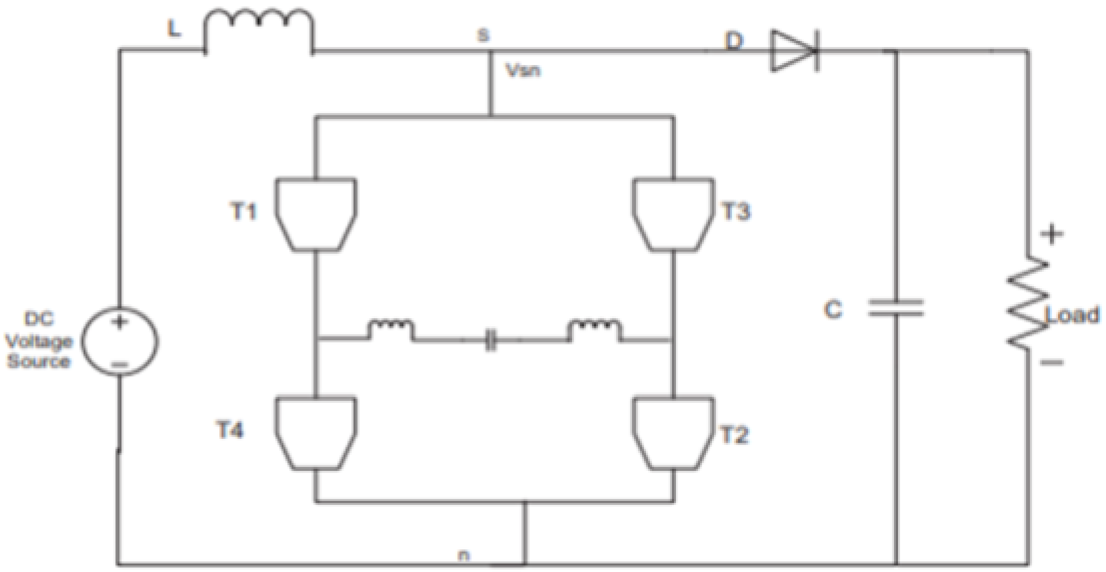


Figure 30 Boost derived hybrid converter as proposed in [116]

Reconfigurable port non-isolated MPCs use relays and other slow switching devices to allow conventional converter configurations to interface multiple ports. Their simple construction possesses a low device count that offers high efficiency and power density. However, the slow switching doesn't support high operational flexibility on short timescales as the change between power flow modes can be slow and sluggish.

[115] proposes a single-stage three-phase reconfigurable converter, which is pictured in Figure 31. The PV and ESS are collocated on the DC bus and are interfaced to the grid via a conventional three-phase inverter. The reconfigurable inverter is capable of power flow bidirectionally between the grid and battery or unidirectionally from the PV to either other system, where the power flow modes are chosen by opening and closing the corresponding switches that interface each device.

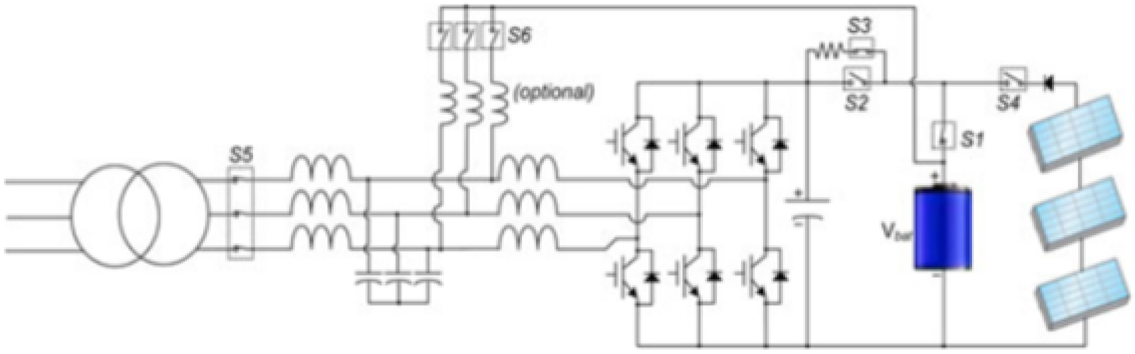


Figure 31 Reconfigurable three-phase inverter as proposed in [115]

Multiport converters are mainly based on AC or DC parallel-connected ports, but topologies with series-connected ports can be also considered. In particular, the Unified Power Quality Conditioner (UPQC) is a combination of a parallel-connected and series-connected converters, which are at the same time interconnected usually as a back-to-back configuration as shown in Figure 32. Such device represents a two-port converter that can independently exchange reactive power at each port and exchange active power between both ports. The series-connected port can control line voltages and power flow with a partially-rated converter. The parallel- or shunt-connected port can compensate reactive power and regulate bus voltages. The active power exchange between the ports can be used for voltage and power flow regulation.

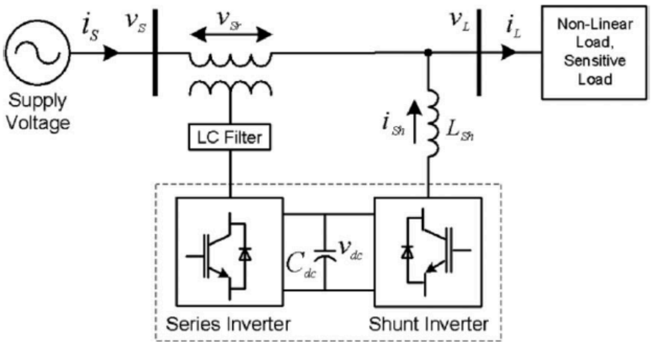
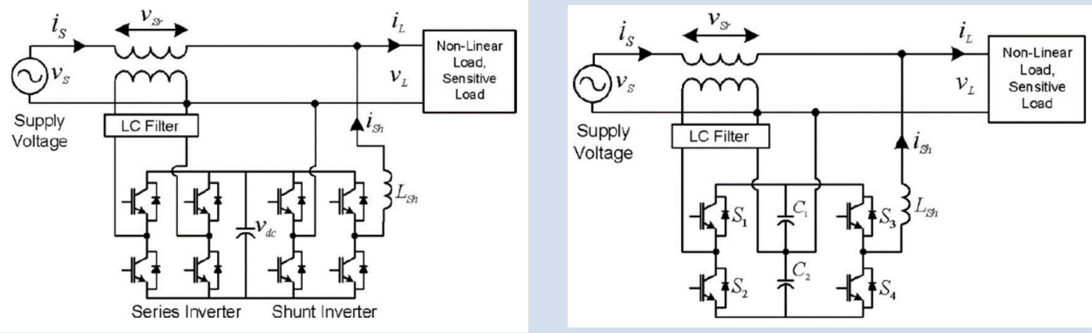


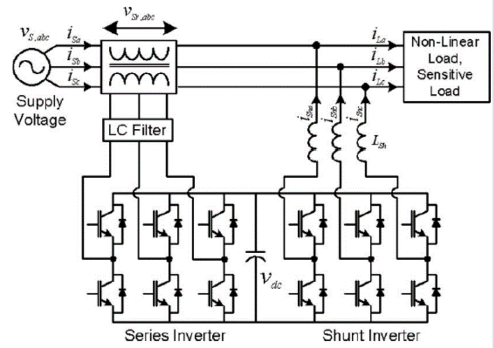
Figure 32 Structure of UPQC

The UPQC is presented as a device for distribution grids, where the main applications are voltage regulation, power losses minimization and power quality improvement [127], [128]. An equivalent structure is also presented for transmission grids, where this converter is called Unified Power Flow Controller (UPFC) [127], [129]. The differences between the UPQC and UPFC are mainly in the topologies and grid services that provide. Alternative names for the UPQC used in MV applications are found in the literature as distribution-UPFC (D-UPFC)[130] and Smart Power Bridge [131]. UPQC topologies can be based on conventional two-level VSC, as presented in [128]. Figure 33 shows some alternatives for single-phase and three-phase system.



(a) Single-phase topology based on H-bridge configuration [132]

(b) Single-phase topology based on half-bridge configuration [133]



(c) Three-phase topology [134]

Figure 33 Possible UPQC topologies

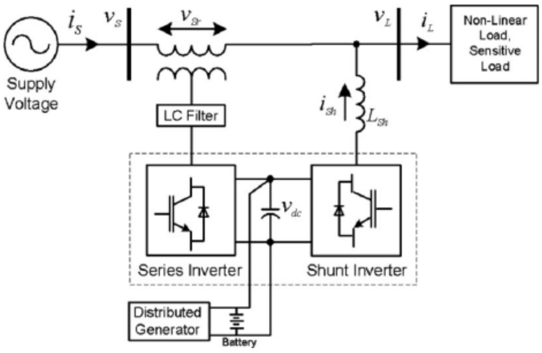


Figure 34 Multiport UPFC considering distributed generation

Multiport topologies of the UPQC structure with multiple series- or parallel-connected ports have been also suggested in the literature to introduce storage and distributed or renewable generation [128], as shown in Figure 34.

6.3.2 Isolated

6.3.2.1 Multi-winding single transformer

Multi-winding single transformer MPC is a topology that offers benefits such as galvanic isolation, modularity, and fault tolerant operation. This topology allows the integration of multiple sources and loads through multiple windings connected to a single medium or high-frequency transformer. This type of power converter is constructed by a set of DC-AC modules (usually a full-bridge) connected to a reactive network, which in turn is connected to the high-frequency transformer. The last, couples magnetically all the reactive networks from the input to the output side. Furthermore, if bidirectional power flow is assumed, the input and output reactive networks are interchangeable [100]. One of the main advantages of this type of converters is the high voltage gain obtained by the use of the transformer [102]. However, it could be hard to deal with the magnetically coupled ports, as undesired coupling creates circulating currents, which could significantly decrease the converter efficiency if are not well managed.

When referring to the reactive networks, they could be of two different types: resonant or non-resonant networks. In general, the well-known DAB and series resonant LLC (SRC) converters are considered the building blocks of the isolated multi-winding non-resonant and resonant topologies, respectively. Furthermore, isolated multi-winding converters inherit notable benefits from the DAB and SRC, such as soft-switching, high efficiency, and high power density [100]. However, these multiport topologies are non-linear MIMO with a high degree of unwanted coupling between states, which makes its modelling, analysis, and control a complex task [104].

Non-resonant topologies based on the DAB are the most popular in the literature. This topology is mostly considered when output voltage and power flow control are needed for multiple energy sources integration, while obtaining a compact structure and lower cost [6]. A detailed description of the multiple active bridges (MAB) and their mathematical model is provided in [106], where a quad active bridge (QAD) is employed to build a solid state transformer connecting the grid to distributed energy sources and the load. Despite their aforementioned benefits, in non-resonant topologies, the power transmitted is inversely dependent to the inductance impedance, which creates a much more obvious constraint for switching frequency selection when compared to resonant topologies. On the other hand, resonant topologies could realize higher switching frequencies [103]. Also, resonant topologies are a better option when output voltage regulation under highly variable loads is needed [100].

Another proposed classification of the multi-winding MPC is by its architecture symmetry [100]. This classification depends on how the port bridges are coupled in the transformer. If the bridges are coupled equally on each side, as depicted in Figure 35 (a), the converter is classified as symmetric. On the other hand, asymmetric converters are the ones that couple unequally the port bridges in the transformer, as shown in Figure 35 (b).

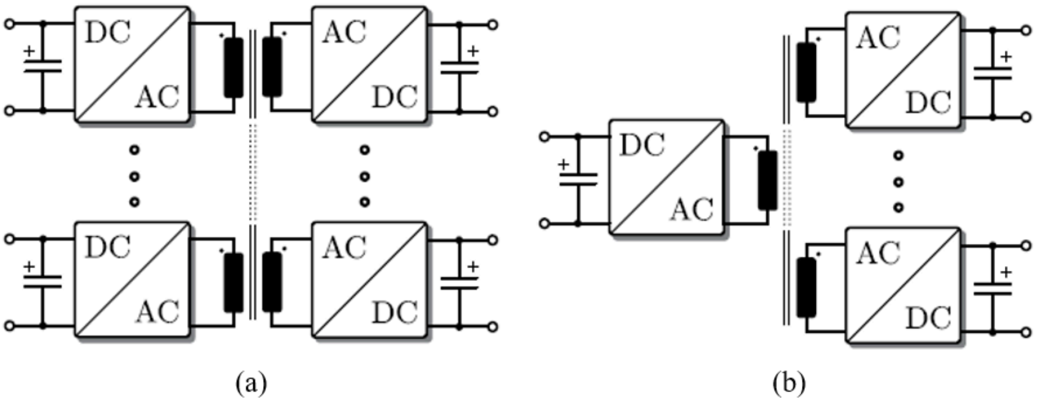


Figure 35 Symmetry of multi-winding single transformer converters [100]

The main advantages, challenges, and disadvantages of multi-winding isolated topologies are listed as follows.

Advantages:

- Lower core material and volume when compared to single winding multi-transformer MPCs.
- Lower switching devices (and lower switching losses) than in the single winding multi-transformer MPCs (for some particular applications).
- Asymmetrical configurations could further reduce the number of switching devices (when compared to symmetrical ones), leading to lower cost and losses, and increasing the power density. This claim is valid under specific applications and design needs.
- Fault tolerant capabilities are larger than in the single winding multi-transformer MPCs. The faulty port winding could be isolated/disconnected from the transformer.
- Non-resonant topologies have higher degrees of freedom, which allow to control power flow, output voltage and other desired conditions such as an increased soft-switching range.

Challenges:

- Difficult to scale. If ports are added, then the control and management rules should adapt to new operating conditions.
- Unwanted magnetic coupling between ports.
- Stray elements deviation between transformer theoretical and real values.
- In resonant topologies, lower degrees of freedom limits power flow control realization.

- Interconnection between input and output ports (series, parallel, independent) affects the reactive network behaviour in the transformer windings, which could emphasise or diminish the unwanted coupling effects.

Disadvantages:

- Asymmetrical topologies need semiconductor devices with lower conduction losses to achieve the same efficiencies than symmetrical ones.
- Single isolated port failure leads to converter failure, and no degraded operation could be done.
- More devices per converter (compared to single port converters) increases the chances of failure and degraded operation.
- Unwanted coupling between ports leads to higher circulating currents in the converter and higher unwanted and inefficient power transfer.

6.3.2.2 Single winding multi-transformer

Multi-transformer MPC are less explored in the scientific literature and the main topologies that can be found are three:

- Modular multi-active bridge (MMAB);
- Dual transformer triple active bridge (DT-TAB);
- CLL resonant converter.

MMABs are the variant of Multi Active Bridges (MABs) with multiple transformers. The main difference between MMABs and MABs is their modularity. One of the disadvantages of MABs with a single core is that once they are built and their control designed, it's hard to change them to accommodate new ports or remove unneeded ones. MMAB provides a solution to this problem by connecting "standard" modules, each of which is composed by a full bridge, a series inductance and a transformer (pictured in Figure 36). This topology should also enhance scalability and allow the connection of the modules in different ways [110]. Regarding the control design, it may be complicated due to the high interdependence between the modules. However, in [108], the small-signal model of MMABs is introduced with the aim of decoupling the control loops. A recent work [112] explores the problem of high frequency oscillations in MMABs and proposes two solutions: a passive voltage clamping method and an active selected-harmonic-elimination general-phase-shift modulation (SHE-GPS).

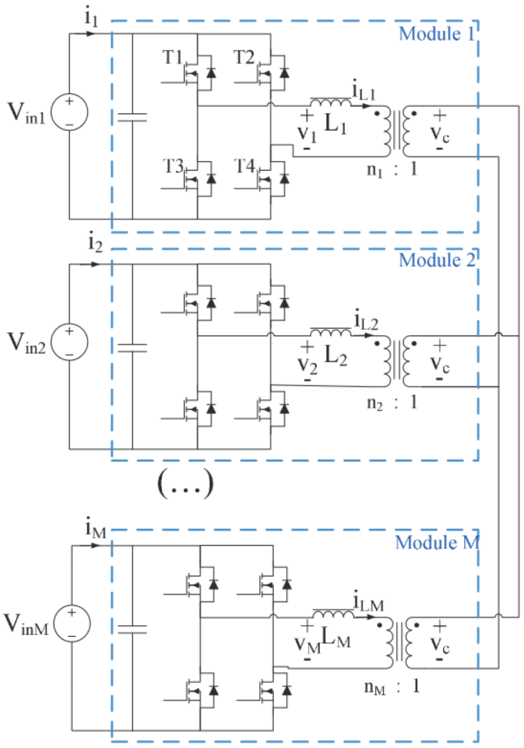


Figure 36 Modular multi-active bridge [108]

Dual-transformer TAB (DT TAB) is the multi-transformer version of the TAB, the authors of the papers claim that it has many advantages compared to multi-winding TAB, including:

- Lack of circulating power between source port;
- Potential simultaneous power delivery from sources;
- Reduction of inrush currents in the transformer;
- Improved lifetime;
- Reduced losses.

In the literature two main topologies can be found: symmetrical [111] and asymmetrical one [5], based on the number of switches of the source ports and load port.

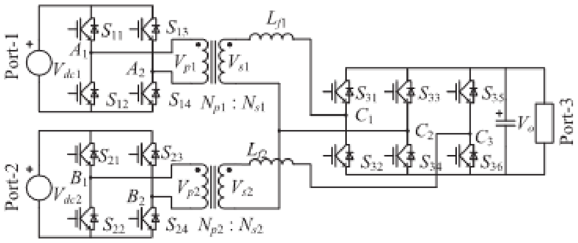


Figure 37 DT-TAB (asymmetric) [5]

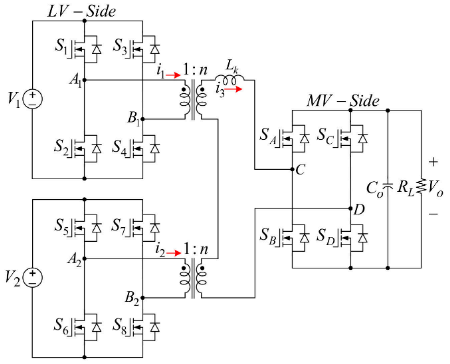


Figure 38 DT-TAB (symmetric) [111]

The CLL resonant MPC is made up of half bridge separated CLL resonant converters on the primary and a single-phase bridge rectifier on the secondary [109]. The main advantages of this topology are the soft switching (either Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS)) at high operating frequencies, wide input and output voltage ranges and a simple filter structure. The authors of the associated paper claim that the controller design for this converter is easier if compared to the other topologies.

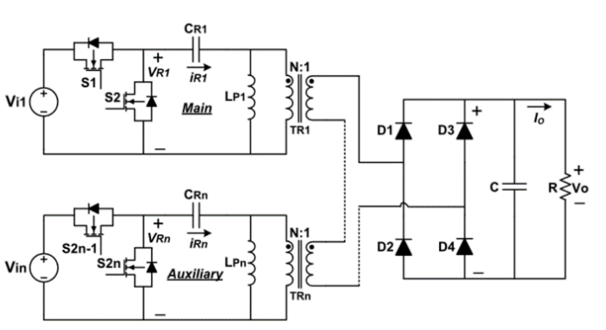


Figure 39 CLL resonant converter [109]

6.3.3 Partially isolated

Partially Isolated MPC group of systems topologies involve all configurations that provide integration of three or more devices using at least two power conversion stages. These are typically based on one isolated conversion stage and another one non-isolated.

Partially isolated MPCs can be classified based on how isolation is realized into two groups: non-integrated isolation and integrated isolation. In non-integrated isolation topologies, DAB or resonant converters are employed as an additional stage converter to provide isolation. The integrated isolation topologies integrate an isolation converter as: DAB or resonant converters into the main topology without cascaded connection of converters.

6.3.3.1 Non-integrated isolation

The following topologies are developed by series connection of two converters: AC-DC voltage source converter and DC-DC converter for isolation.

[118] proposed a partially isolated two-stage ac–dc–dc converter containing an isolated DAB dc–dc converter and an ac–dc rectifier connecting the dc sources to the ac utility grid.

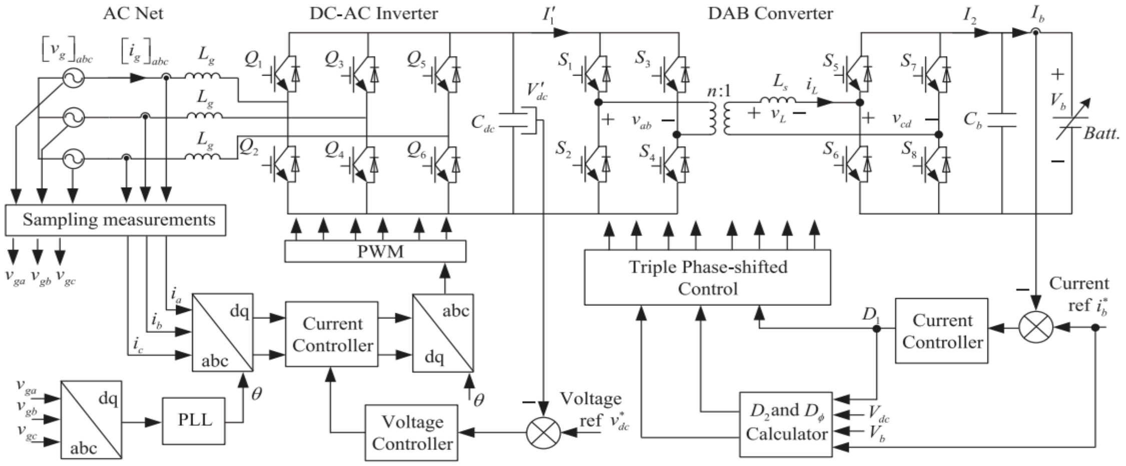


Figure 40 Topology and closed-loop control configuration of the two-stage AC-DC-DC converter [118]

[119] adopted a cascaded two-stage combination of a three-phase six-switch power factor correction and phase-shifted full-bridge (PSFB) dc/dc stage.

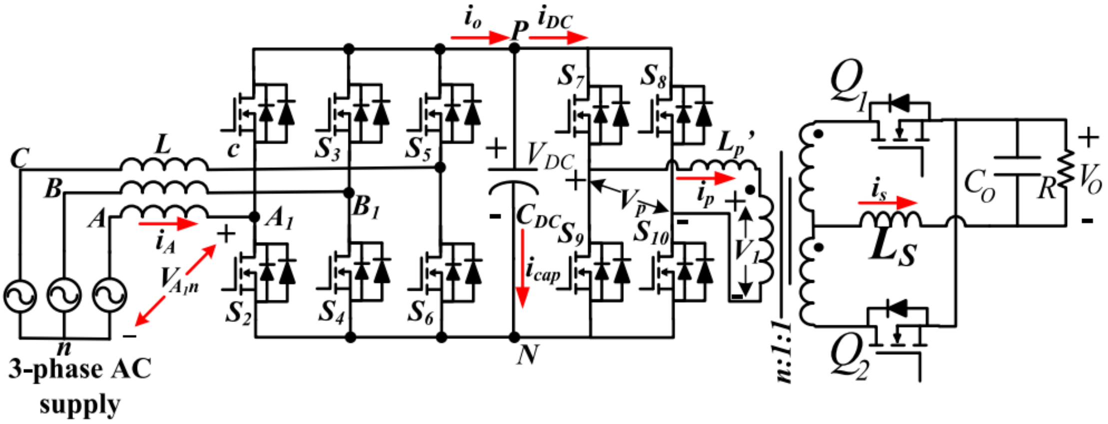


Figure 41 Structure of the integrated three-phase boost PFC and PSFB converter [119]

[120] proposed a two-stage ac-dc power supply for battery charge application. In this developed two-stage structure, 400 V three-phase three-level T-type PFC ac-dc input stage is followed by an isolated dc-dc buck converter as an output stage.

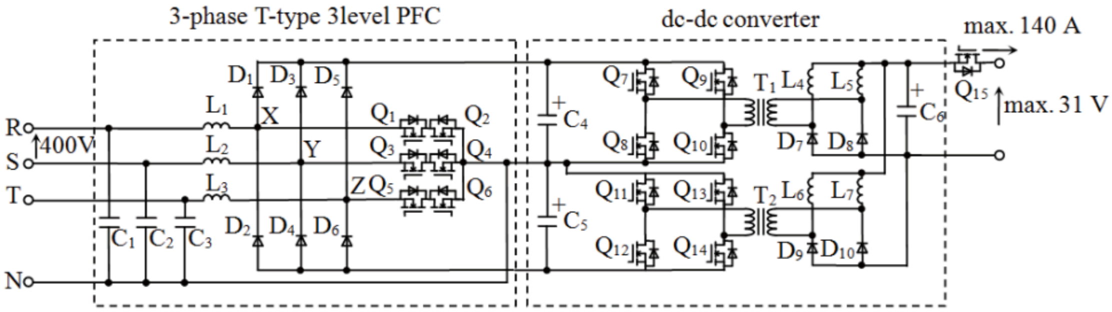


Figure 42 Circuit configuration of three-phase three-level T-type battery charger [120]

Advantages:

- Simple configuration and control
- Ease of adding extra ports
- Decoupling between ports using the DC link capacitor and isolation transformer
- Fault isolation

Disadvantages and challenges:

- Efficiency degradation due to cascaded connection of converters
- Need for a high DC-link capacitance
- Impedance interaction between the AC-DC converter and DC-DC converter

6.3.3.2 Integrated isolation

[122]proposed the Dual Three-Phase Active Bridge (D3AB) converter topology as a multi-port converter, by taking the three-phase ac port and dc port on the primary side (ac 1 and dc 1) and the galvanically isolated three-phase ac port and dc port on the secondary side (ac 2 and dc 2) simultaneously into account.

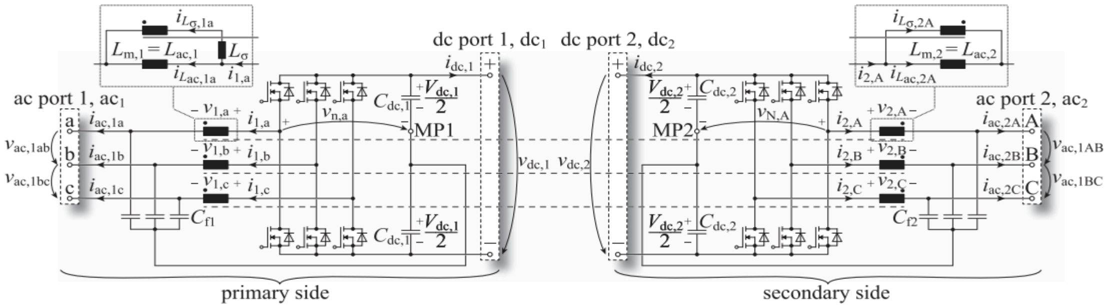


Figure 43 Topology of the dual three-phase active bridge (D3AB) with primary side AC and DC ports (ac$_1$, dc$_1$) and galvanically isolated secondary-side AC and DC ports (ac$_2$, dc$_2$) [122]

[123] proposed a three-phase, single-stage, isolated ac-dc converter that employs only two switches provides a tightly regulated, isolated, output voltage is introduced. The rectifier features zero-voltage-switching of both switches over the entire input and load range without any additional soft-switching circuitry. The rectifier is derived by combining the three-phase, power-factor-correction, discontinuous-current-mode boost rectifier that is also known as Taipei rectifier with the conventional LLC resonant half-bridge converter.

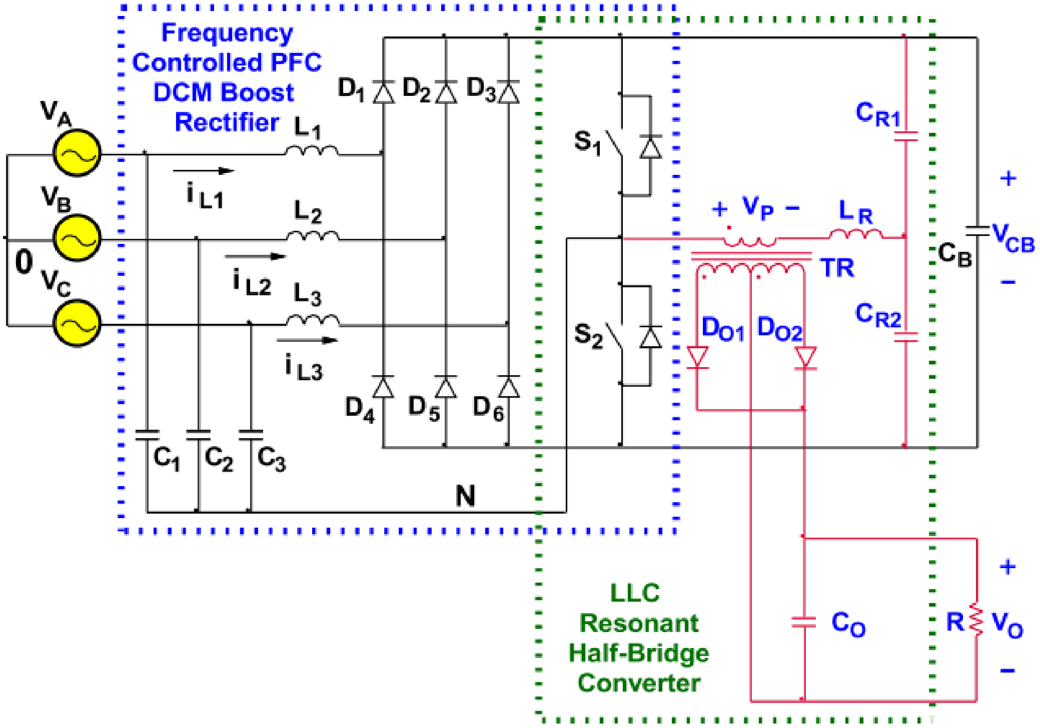


Figure 44 Two-switch isolated three-phase rectifier [123]

Advantages:

- Reduced number of semiconductor devices
- Reduced DC link capacitance

Disadvantages and challenges:

- Complex configuration and control
- Adding extra ports is more complex

6.3.4 Examples of multiport power converters for medium voltage applications

The discussion so far has focused on topology review on low voltage applications. However, the advantages and disadvantages of the non-isolated/isolated topologies as discussed still stands. For this application, a series connection of multiple submodule cells is important to have modularity in terms of voltage levels. From the initial study in WP1, the solution to look at focuses on the use enhanced soft-open point, where the number of ports can be adapted as required. In the following, three examples are discussed as a suggested start-up solution for medium-voltage grid application as the case study suggested in WP1. It consists of two medium voltage ac-ports of different voltage levels connected back-to-back and one dc-port to host either PV or energy storage.

6.3.4.1 Non-isolated

The main building block of the topology in Fig. M1 is the back-to-back connection of the ac-ports. These are made of series connection of half-bridge cells, and this allows to generate any voltage level on the ac ports [117]. Therefore, there will be a common medium dc-link voltage that decouples the two ac-voltage levels. This voltage provides the dc-port for integration of energy storage or PV. As the energy storage and/or the PV must be connected at a lower dc-voltage, a DC/DC converter (isolated or non-isolated) can be used.

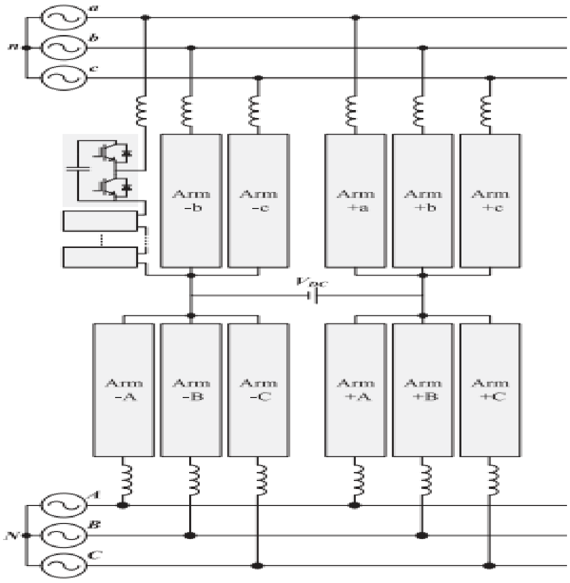
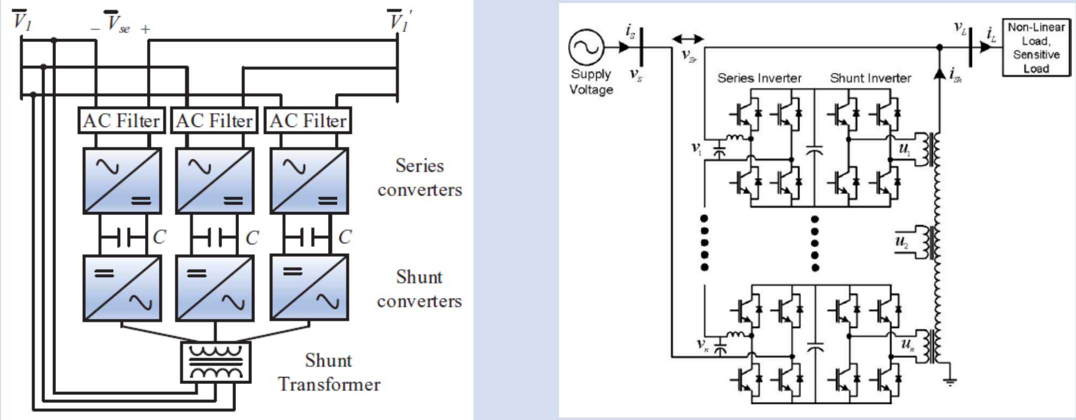


Figure 45 Back-to-back modular multilevel converters as a soft-open point [117]

Multiport converter topologies with series-connected ports for MV distribution grids are not analysed in the literature, but they can be found for HV transmission grids as reported in [135]. Also, several topology suggestions are presented for the two-ports device, i.e. the UPQC. Multi-level VSC topologies have been explored, in particular diode-clamped [136], neutral-point-clamped [137] and flying capacitor converters [138]. The series-connected port of a conventional UPFC requires an interfacing transformer that should withstand line short-circuit current and should have a magnetic core with over-excitation tolerance. However, alternatives without transformer that employ three single-phase converters have been suggested for MV applications [131], [139], as shown in Figure 46 (a). Also, modular multilevel VSC can be used to eliminate the series transformers, as presented in [128], and shown in Figure 46 (b).



(a) UPQC with three single-phase converters [139]

(b) UPQC with modular multilevel structure [121]

Figure 46 UPQC configurations without series transformer

6.3.4.2 Isolated

For connecting the two ac-ports, a matrix converter from cascaded connection of full-bridge cells can be employed. This however will not offer the possibility of an extra dc-port. To achieve this, a medium frequency transformer with an LC resonant as shown in Figure 47 can be used [107]. The transformer provides the flexibility to have an extra port in addition to the isolation between the ports. To reduce the overload over the single transformer, multiple resonance circuits and multiple transformer solutions can be also investigated.

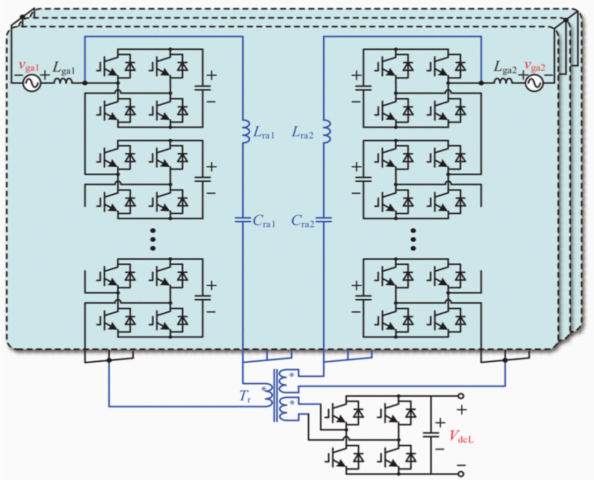


Figure 47 The proposed multiport AC-AC-DC converter with one MFT [107]

The final option is to use modular smart transformers as in Figure 48 This option gives all the flexibility and reliability for the application at a cost of high component count and hence cost. The DC/DC converter architecture can also be based on QAB or MMAB units and each option varies in its advantages and disadvantages as described in previous sections [105], [113], [140].

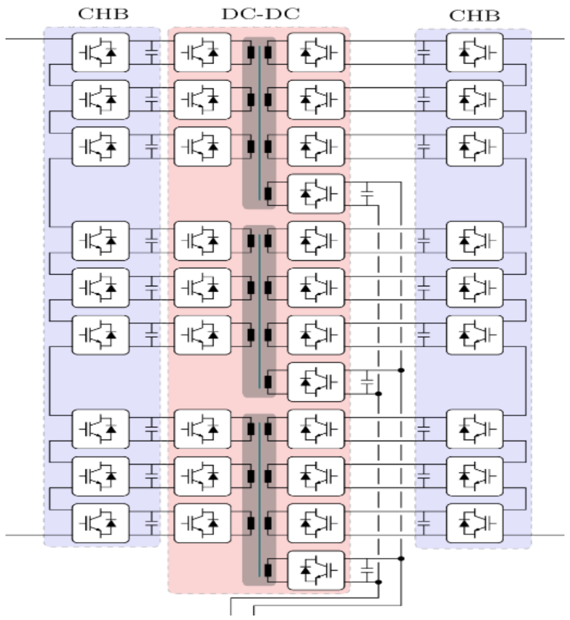


Figure 48 Modular ST architecture using the DAB converter as a building block of the DC-DC stage [113]

6.4 Results of Pugh Matrix Scoring

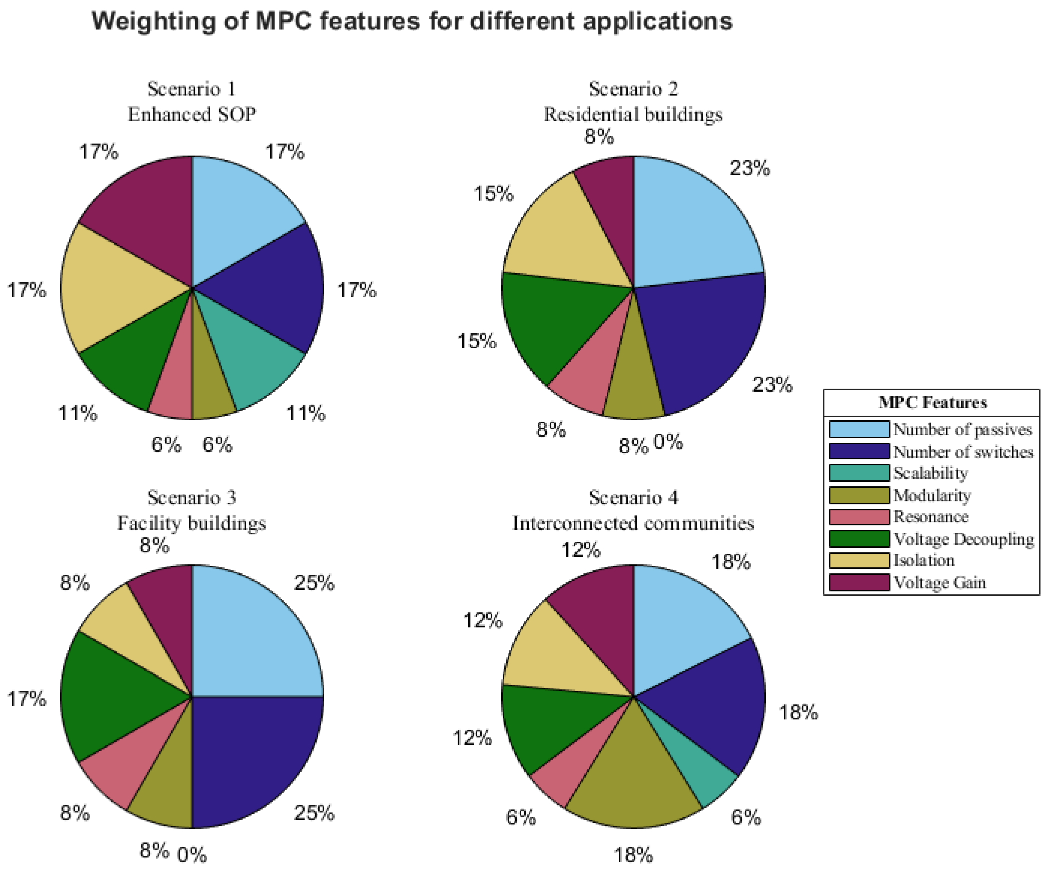


Figure 49 Weighting of MPC features for the iPLUG scenarios

Figure 47 depicts the proportional breakdown of the weights for each scenario and hence the importance of the different features for the different applications. Despite the number of switches and number of passive devices always being allocated the same weight (3), the importance of the other features changes between scenarios. As a result, the scenarios which require additional functional capability (e.g. isolation, voltage decoupling, voltage gain, etc.) put less proportional weight on the number of devices. For example, only 34 % of the total score for Scenario 1 is contributed from the number of switches and passives. In contrast, the suitability for lower voltage applications that require less advanced functional capability depends more highly on the number of devices (e.g. 50 % of Scenario 3’s total score depends on the number of switches and passive devices).

6.4.1 Scenario 1 Enhanced SOP

Scenario 1 is defined to require 3 ports, two of which are bidirectional ports for MV AC feeders, and one unidirectional DC port for a Solar PV farm. It is allocated equal maximum weights for voltage gain, isolation, number of switches, and number of passive devices. It is allocated a weight of two for voltage decoupling and scalability and a weight of one for resonance and modularity. The total scores of the reviewed topologies (and their breakdown in terms of feature contributions) are pictured for Scenario 1 in Figure 48.

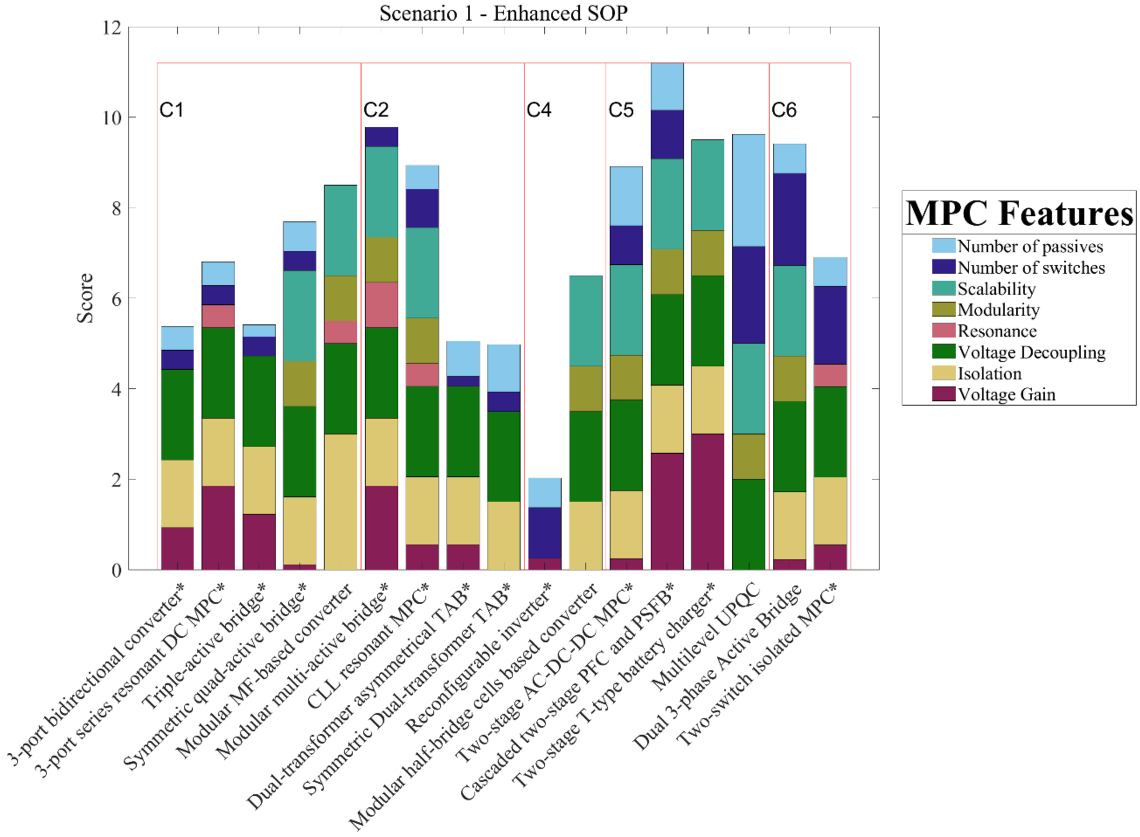


Figure 50 MPC topology scores for iPLUG Scenario 1. Topologies are arranged by isolation class, which is introduced in Figure 1. Topology names that are marked with an asterisk only qualify for Scenario 1's requirements using additional inverters.

Most of the reviewed topologies can be made to fit the port specification and therefore qualify for Scenario 1's enhanced SOP application. Many of the DC output MPCs are adapted to interface to the AC ports using additional inverters, indicated by an asterisk in the topology name in Figure 50. However, none of the non-isolated DC MPCs (C3) are capable of meeting the specifications due to the low flexibility of their ports to support sufficient bidirectionality. The two most flexible AC and DC capable non-isolated MPCs (C4) qualify to meet the SOP specifications but receive low scores either due to weak operational features or a large number of switches and passive devices.

Isolated topologies (C1 and C2) are reasonably suited to operate as enhanced SOPs, however, their scores are generally reduced due to low recorded voltage gains and high numbers of switches and passive devices. The modular MF based converter is very suited to the SOP application and is the only topology that would offer full isolation between all ports (considering that fully-isolated DC MPCs require additional inverters to interface the AC ports). However, its multilevel nature means that 1) an exact number of switches and passives cannot be estimated/scored and 2) the number of switches and passives will increase as the voltage level is scaled up. The modular multi-active bridge topology is explored in several studies and is found to possess modular, scalable, and resonant features [5], [104]–[106], [108], [110]–[113] as well as exhibiting a large voltage gain [108]. The example in Figure 50 achieves a high score despite being offset by the zero score for switches and passive devices due to the scalable multilevel configuration as it accounts for all of the features recorded in the reviewed multi-active bridge studies.

In general, partially isolated MPCs (C5 and C6) appear to be most suited to the enhanced SOP application due to their desirable functionality (isolation, voltage decoupling, modularity, and scalability) in combination with low numbers of switches and passive devices. The difference in scores within the partially isolated topologies is mostly driven by the difference in voltage gain. The cascaded two-stage PFC and PFSB converter achieves the highest total score due to its high voltage gain. However, its score for number of switches and passive devices would degrade if it were scaled beyond the 2-level configuration that is assessed in Figure 50. Other suitable topologies include the multilevel UPQC and dual 3-phase active bridge MPCs, which could both be further supplemented with desirable voltage gains. Overall, the least represented feature in the top scorers was resonance, which could offer a route to further improve these topologies' suitability.

6.4.2 Scenario 2 Residential building

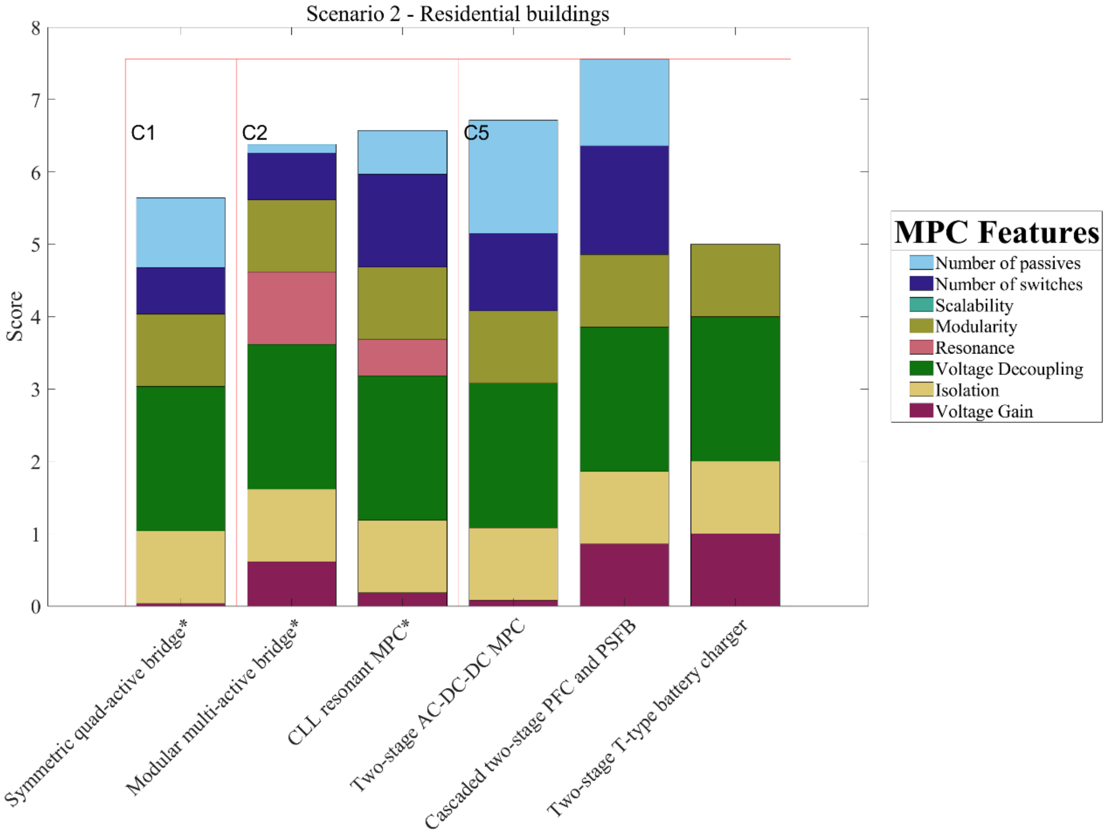


Figure 51 MPC topology scores for iPLUG Scenario 2. Topologies are arranged by isolation class, which is introduced in Figure 1. Topology names that are marked with an asterisk only qualify for Scenario 2's requirements using additional inverters.

Scenario 2 requires the MPCs to possess four ports, two of which need to be bidirectional (the DC ESS and LV AC feeder) and two of which can be unidirectional (the DC Solar PV and EV charging ports). Less weight is assigned to Scenario 2 in terms of voltage gain and scalability due to its lower voltage environment. However, isolation is still highly desirable for the EV charging port [93], as is voltage decoupling for the interfacing of a RES with an ESS. The lower score contribution from functional features means that the number of switches and passive devices plays a key role in Scenario 2's overall score. The scores and feature breakdown for topologies for Scenario 2 are pictured in Figure 51.

A low number of topologies qualify for the residential building application. The reviewed non-isolated topologies (C3 and C4) could offer suitable solutions if the residential application were just to include the conventional combination of ESS, Solar PV, and LV AC feeder. However, none of these non-isolated topologies are capable of meeting the additional requirements to interface the EV charger due to their low design flexibility.

The topologies that do qualify for Scenario 2 achieve reasonably similar scores as one another. The qualifying topologies are either isolated (both C1 multi-winding single transformer and C2 single winding multi-transformer) or non-integrated partially isolated (C5), many of which perform equally well in terms of voltage decoupling and modularity. The fully isolated topologies that require inverters to meet the scenario specifications receive an equivalent score as the partially isolated topologies. The remaining variation in scores results from voltage gains, resonant ability, or number of switches and passive devices. Once again, the cascaded two-stage PFC with PSFB converter achieves the highest score for this application as a result of its low number of devices and good voltage gain.

6.4.3 Scenario 3 Facility building

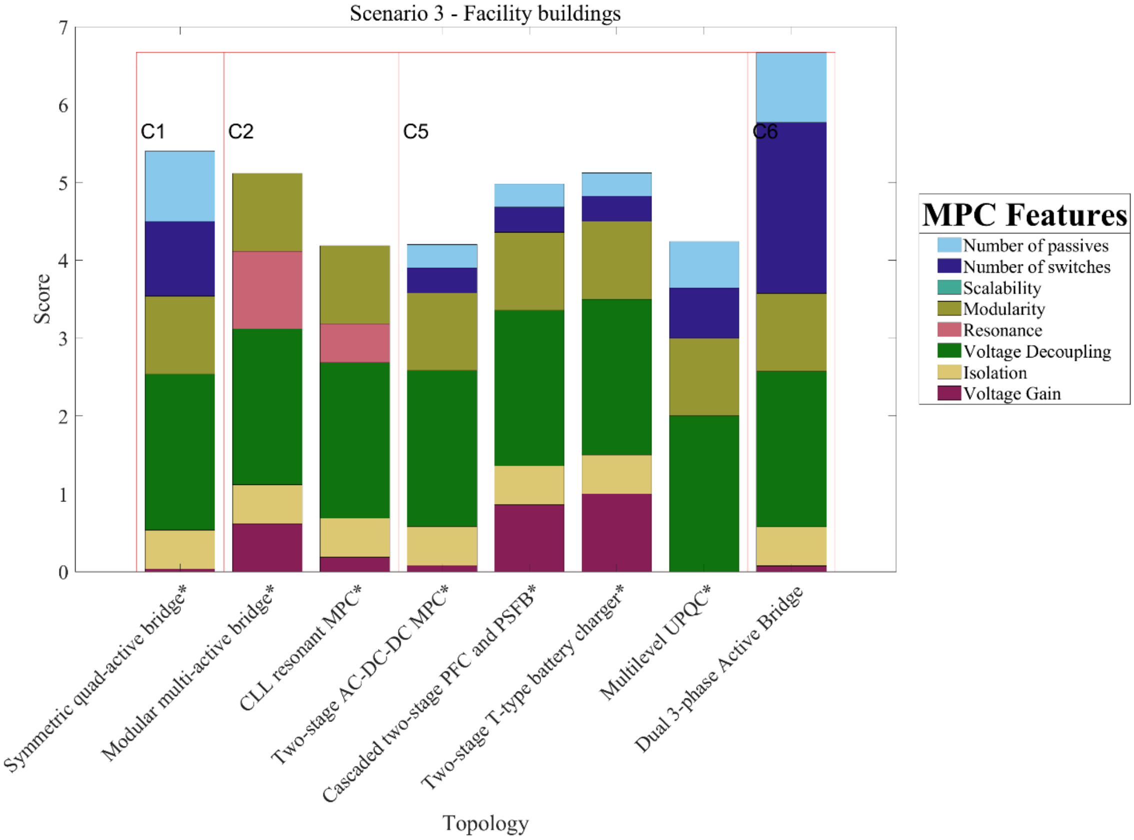


Figure 52 MPC topology scores for iPLUG Scenario 3. Topologies are arranged by isolation class, which is introduced in Figure 1. Topology names that are marked with an asterisk only qualify for Scenario 3's requirements using additional inverters.

Scenario 3 requires MPCs to possess five ports, two of which are bidirectional (LV AC feeder and DC ESS) and three are unidirectional (LV AC load, AC diesel generator, and DC Solar PV). Scenario 3's feature weights are similar to Scenario 2's, although a larger portion of the score is allocated to the number of switches and passive devices due to the lower allocation of score to isolation. The scores and breakdown of features of topologies for Scenario 3 is pictured in Figure 52.

A similar range of topologies qualify for Scenario 3 as Scenario 2 due to the similar qualifying features. Non-isolated topologies are disqualified due to the need for multiple bidirectional ports. Two additional partially isolated topologies (the multilevel UPQC and the dual 3-phase active bridge) qualify for the facility building application due to the increased number of AC ports.

The topologies receive reasonably consistent scores for Scenario 3 for features such as isolation, voltage decoupling, and modularity (also similar to Scenario 2). As a result, the differences in score between the topologies that qualify for Scenario 3 are mostly driven by differences in voltage gain and the number of switches and passive devices. Only the dual 3-phase active bridge topology can be adapted to fit the Facility building specifications without the use of an additional inverter. As a result, this topology provides the required functionality with the lowest number of switches and passive devices and achieves the highest total score. Its score could be improved further if its voltage gain was improved and/or if it was adapted to achieve resonant capability, which could increase its operational efficiency.

6.4.4 Scenario 4 Remote community

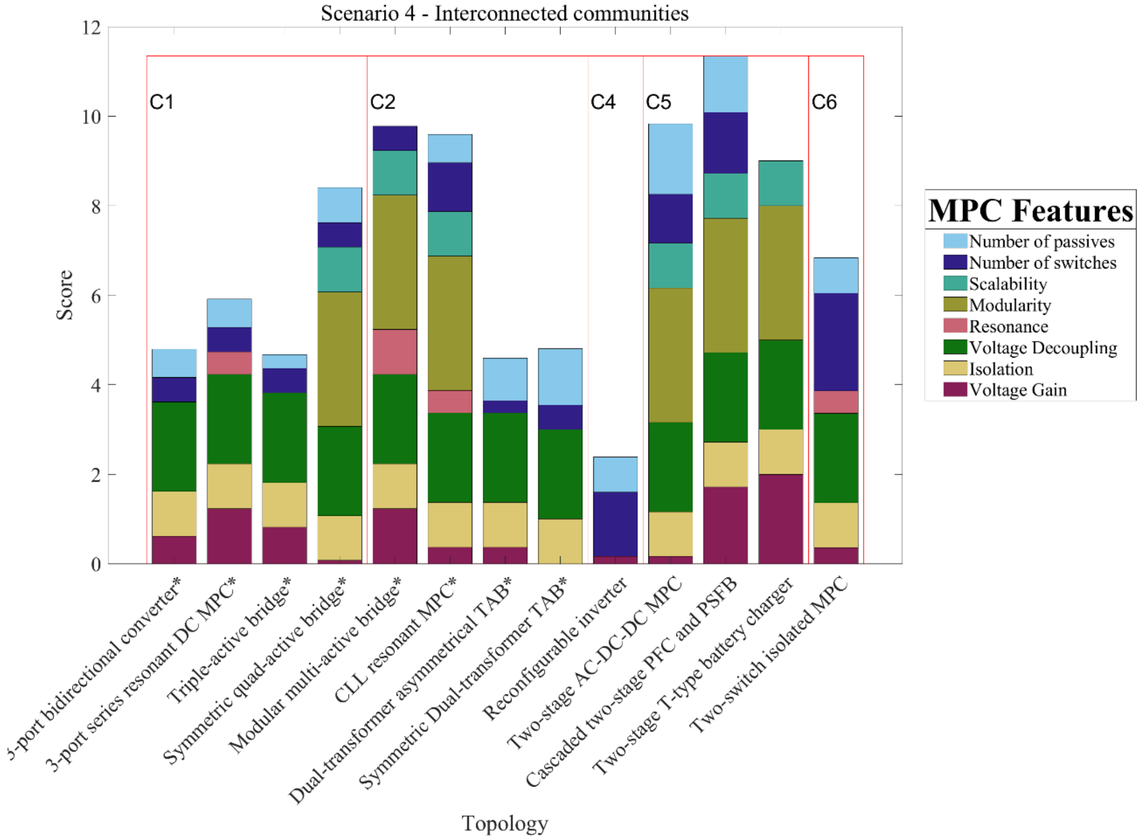


Figure 53 MPC topology scores for iPLUG Scenario 4. Topologies are arranged by isolation class, which is introduced in Figure 1. Topology names that are marked with an asterisk only qualify for Scenario 4's requirements using additional inverters.

Scenario 4 requires MPCs to interface 3 ports, two of which are bidirectional (a LV AC feeder and a DC ESS) and one of which is unidirectional (the LV Solar PV). Although not a qualifying requirement, the scenario assigns the highest possible weight to modularity as an additional MV AC feeder is expected to be connected during future MV grid expansion to the remote community. Due to this planned MV interconnection, Scenario 4 also possesses high weights for voltage gain, voltage decoupling, and isolation. The scores and breakdown of feature contributions of topologies for Scenario 4 is pictured in Figure 53.

A large number of topologies qualify for Scenario 4 due to the initially low number of required ports. These qualified topologies include the non-isolated reconfigurable port topology. However, this non-isolated topology receives a low overall score due to its lack of desirable operational features. Of the remaining qualified isolated and partially isolated topologies, there is a large range in score.

The next lowest scores above the non-isolated topology are recorded for isolated topologies without modular or scalable capabilities. These topologies include: the 3-port bidirectional converter, the 3-port series resonant DC MPC, and the different TAB variations. The highest scoring isolated topologies are the modular multi-active bridge and the CLL resonant MPC, where the former benefits from multi-resonance and the latter benefits from a lower number of switches. Despite their higher device number, these isolated topologies achieve similar scores as the best performing partially isolated topologies such as the two-stage AC-DC-DC MPC and the two-stage T-type battery charger, which don’t possess resonant capability. However, the two-stage PFC with PSFB records the highest overall score again due to its high voltage gain and low number of devices. In general, all of the partially isolated topologies could explore resonance as a potential route to improve their performance.

6.5 Discussion

Overall, the partially isolated topologies offer a good balance between operational flexibility, desirable functionality, and low numbers of devices for the given specifications. As a result, these topologies (the two-stage AC-DC-DC MPC, the cascaded two-stage PFC and PSFB, the two-stage T-type battery charger, and the dual 3-phase active bridge) perform consistently well for most of the assessed scenarios. The highest scoring topology for each specific scenario varies depending on the suitability of the fundamental converter topology to the port requirements, which then translates to a better score for fewer switches and passive devices.

Some isolated topologies, such as the modular multi-active bridge and CLL resonant MPC, also perform well, although they lose their full isolation between ports as a result of additional inverters being added to meet the AC port requirements. In general, the low-flexibility of the non-isolated topologies to provide multiple bidirectional functionality or for ports to be added or scaled up results in them either not qualifying or scoring poorly in most scenarios. Had the Residential or Facility building Scenarios 2 and 3 simply required 2 DC ports (for a Solar PV and ESS) and 1 AC port (for LV AC feeder), these non-isolated topologies may have performed well considering their low number of devices for these less strenuous applications.

Further research should be focussed on proving higher voltage gains to support the integration of different devices and adding resonant ability to improve the efficiency of MPC operation. However, considerations will have to be made to validate that this added functionality comes as a net benefit to the MPC’s feasibility considering the potential cost of additional devices. Moreover, many isolated and partially isolated topologies were allocated large scores due to their modular and scalable capabilities, however, these features will inherently be associated with the addition of switches and passive devices. Specific analysis needs to be made to optimise the scaling of ports to support the cost-effective integration of different voltage levels.

This analysis serves as an initial overview of a range of topologies’ suitability for different applications. It attempts to provide a justified overview of the variation in useful features for different scenarios and to highlight the topologies that have potential in these applications. The analysis uses information gathered from a literature review of topologies that are designed and tested in different conditions, so will inherently include some inaccuracy. However, it can also serve to provide justification for the iPLUG consortium to pursue further research and analysis on some of the mentioned isolated and partially isolated topologies.

7 Communication and Hardware to Control the MPC

Consideration of communication technology is fundamental before establishing appropriate MPC design.

Section 3 reveals study cases where MPC is needed to integrate appliances such as Electric Vehicle Charging Points or Renewable Energy Systems which currently rely on some communication standards, primarily used for optimal monitoring and control [141]. As such, Section 7 focuses mainly on comparison of communication protocols currently used for each of such devices which are broadly deployed at different levels of our power systems. Each of them incorporates certain standards that are required to be considered by the iPLUG consortium before finalising MPC architecture.

The list of devices/appliances selected for further analysis in Section 7 is presented below:

- Distributed Resources including Battery Energy Storage Systems (BESS) and Renewable Generation
- Microgrids in Developing Countries
- Smart Meters at the Household Level
- Electric Vehicle (EV) Charging Points

Communication technologies deployed under each configuration investigated in this chapter are required to support either internal, external or both types of data transfers. Internal communication infrastructure is used to share data between different modules under a single arrangement (for example BEES where communication is established between the central control unit, power inverter and Battery Management System). Other devices investigated support external data transfers to send and receive parameters from the centralised back-end device (such as Smart Meters).

Detailed explanation of how communication supports appliances that are expected to be incorporated within the MPC is listed in Section 7.1 of this chapter. Comprehensive review of the main features provided by each of the communication technologies incorporated in selected devices is presented in Section 7.2.

Other aspects essential while designing MPC and covered in Chapter 7 are related to control architecture. In order to achieve desired functionality of power converters, it is needed to have a central control unit managing power converters. Such device needs to collect measurements at optimal sampling frequency to further detect performance of the MPC and provide appropriate control commands adjusting operation of power converter switches. This consideration is revealed in Section 7.4 where comparison between FPGA (Field Programmable Gate Arrays) and DSP (Digital Signal Processing) is produced.

7.1 Introduction of Principal Devices supported by MPC

Section 7.1 gives examples of devices which are expected to be integrated under a single MPC arrangement. Each of such devices incorporates some standards to support communication technology. These are presented in sections 7.1.1 - 7.1.4 below.

7.1.1 Battery Energy Storage System (BESS)

BESS is a relatively novel solution while being integrated at the power distribution level. It is typically used to store surplus of renewable electricity in order to utilise it while grid is exposed to power deficits [142]. Standard BMS comprises of several submodules to maintain appropriate operation of the system. Each of them is required to be tuned to another which is often achieved by some internal communication infrastructure. An example presenting a typical BMS architecture is indicated in Figure 54 below.

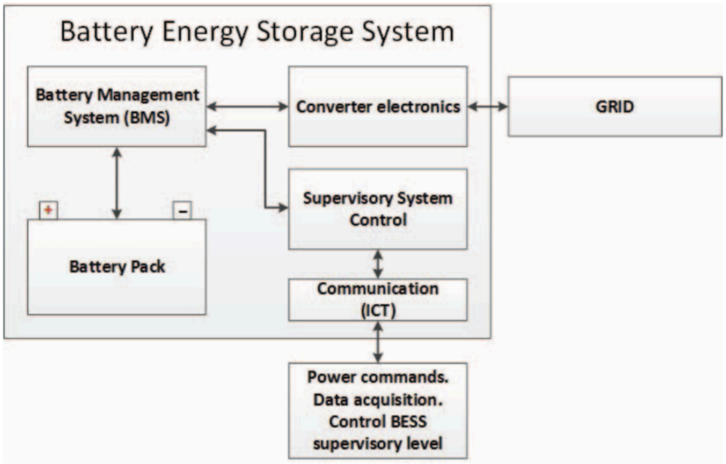


Figure 54 Standard Architecture of BESS.

As presented in Figure 54, typical BESS integrates wide range of modules under a single arrangement [143]. Coordination between them is provided using Supervisory System Control capable to share data with Converter electronics, Battery Management System as well as with external devices.

In order to communicate with a typical BESS using Local Area Network (LAN), it is required to implement Modbus TCP/RTU communication standards [144]. Such capabilities provide user friendly methods to schedule operation of the battery as well as develop appropriate operation strategies used to maximise performance of BESS.

Further studies reveal that internal communication within the BESS used to share measurements between submodules are typically provided using CANBUS protocol. Sections 7.2.1 and 7.2.2 cover the main principles and characteristics of Modbus and CANBUS communication technologies.

7.1.2 Renewable Systems Integration

Installation of solar farm requires communication link to monitor performance of assets deployed at various stages of the power distribution network. Similarly to BMS, solar farms are occasionally exposed to events causing challenges while exporting power to the grid. In order to mitigate these issues, appropriate communication link between the operator and asset gives chance to immediately detect problems and fix them to maximise renewable electricity utilisation factor. To achieve such functionality, many solar charge controllers are equipped with Modbus TCP port providing capabilities to communicate with external devices which are equipped with wireless modules utilising LTE/3G to share data with the centralised server [145].

Example summarizing methodology to arrange communication between solar plants and the planning platform is presented in Figure 55. Such arrangement makes us of TRB140 device to monitor distributed solar assets.

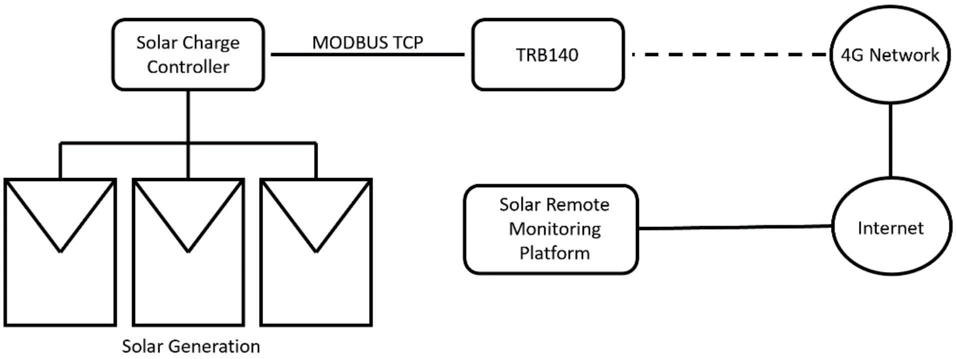


Figure 55 Solar Farm Monitoring Concept.

Alternative solution to monitor household applications is use of WiFi infrastructure which gives opportunity to establish data exchange with a local solar charge controller that manages local photovoltaic farm. This method could be particularly important for installation highlighted in Section 3.4.1 describing MPC integrating solar array, EV, Battery as well as LV network at the household level. In order to build communication link over Wifi between solar charge controller and user interface, Message Queing Telemetry Transport (MQTT) protocol is frequently used. Details presenting its main features are highlighted in Section 7.2.3 of the report.

7.1.3 Off-Grid Microgrids in Developing Countries

Capability to monitor and control off-grid assets in Developing Countries is crucial while providing basic energy infrastructure for people located in the most remote areas around the globe, without access to any modern energy infrastructure. As a result, introduction of appropriate communication channels is fundamental to provide significant development opportunities, especially in countries located in Sub-Saharan Africa [146].

Rapid growth of off-grid assets in the last few years has been noticed particularly due to ability to utilise existing 2G,3G and LTE networks. As a result, local electricity providers have option to disconnect and reconnect customers from electricity supply remotely, according to regularity with which customers pay for energy bills. Similarly, significant adoption of mobile money in Sub-Saharan Africa gives capability to pay electricity fees without need to go to the nearest post office of kiosk which has been supporting rapid expansion of solar microgrid systems across Africa and Asia in recent years.

Data exchange between assets located in rural regions of the Developing World and local system operator can be achieved using Global Pocket Radio Service (GPRS) which is supported by 2G networks [147]. As a result, microgrids are equipped with such modules either in the central location of the network or within smart meters distributed at each household level.

Technology used to communicate with microgrids differs depending on the provider. Previous engagement of University of Strathclyde researchers in rural electrification projects in Sub-Saharan Africa indicate that some microgrid providers such as MeshPower (in Rwanda) have a single point of communication in the network from which signals are shared with the main database [148]. Further demand side management features as well as data collection at the microgrid household level takes place with a support of power line communication (PLC).

Other providers such as Powergen and SteamCo make use of wireless communication infrastructure provided at each household level within a smart meter [149]. This gives more robust configuration and introduces capability for future connection of microgrid to the main distribution network.

Apart from 2G network, some future smart meters in Developing World are expected to be supported by LoRaWAN networks [150], [151]. This way of establishing data exchange with customers located in rural regions of Sub-Saharan Africa is already used by some off-grid systems providers such as SolarWorx [152]. LoRaWAN (Long Range Wide Area Network) is a low cost solution to establish IoT infrastructure which gains significant popularity in recent years, primarily due to its simplicity, robustness and low cost.

7.1.4 Electric Vehicles Charging Stations

Another set of applications frequently listed in case studies (Section 3) considers integration of Electric Vehicles Charging Points. In order to implement appropriate EV infrastructure within one (or more) ports of the MPC it is required to explain the main communication features which charging points are required to follow to sustain all the principal features supporting electric cars.

Electric Vehicle charging infrastructure has been widely adapted in many countries around the world. Such systems are required to provide fast transactions between user and the service provider. In order to achieve this, protocol known as OCPP (Open Charge Point Protocol) is typically used [153]. Data transmission using OCPP can be achieved using internet communication creating a "bridge" between charger and Central Server. Figure 56 summarises the full interaction between charger, EV station Owner, Payment System as well as Driver's App and Central Server.

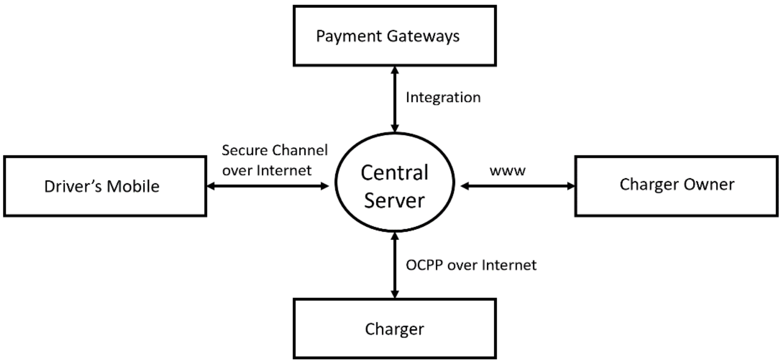


Figure 56 Infrastructure to support EV Charging Systems.

Details presenting operation of OCPP are summarised in Section 7.2.4 of the report.

7.2 Communication Technology for MPC

This section of the report reveals fundamental characteristics of the communication technology required to support appliances connected to MPC and listed in Section 7.1. It starts with a description of the protocols used in the BESS, including Modbus TCP/RTU and CANBUS, following by standards used to communicate with distributed renewable energy systems, off-grid microgrids as well as EV Charging Solutions.

7.2.1 Modbus TCP

Modbus communication protocol was developed in 1979 by Madicon and it became an industrial standard to transfer information between industrial control and monitoring devices [154] . It is now extensively used in a wide range of applications. The communication protocol requires a license which is currently free of charge.

Modbus communication type relies on Master-Slave type of data transfers where just a single device can initiate data exchange. Master requests certain type of data stored under selected registers. Once the request is delivered, selected slave is expected to respond with appropriate data format. Master has also capability to broadcast information to all slaves operating under the same network. In this case, no response is expected from any device receiving data.

To specify Modbus requests and responses it is required to provide appropriate function code, based on standards typical for Modbus [155]. Function codes vary depending on type of data (either discrete or binary), as well as desired purpose. Some function codes are used to change parameters within the slave device, other give capability to read data only. Once function code is selected, address of the registers of interest is needed to be provided by the Master.

The final section of the Modbus frame involves checksum frame used to verify whether data transfer has been exchanged successfully.

Modbus TCP is a standard type of communication with BMS devices using Ethernet cable. It is easily configured with the LAN and could be devices supporting Modbus could be easily identified by other devices connected under the same network.

7.2.2 CANBUS

The Controller Area Network (CAN or CAN BUS) uses two-wires for serial communication. The protocol has capability to share data bidirectionally and is considered as highly robust method for information exchange, often used in car industry to "communicate" with the engine, transmission system or breaks. The physical layer used a pair of twisted cables for data transmission. The messages are short and verified by the checksum [156].

CANBUS allows data transfer based on priority of devices used in a particular device. The main benefits of adapting CANBUS are summarized below:

- Simplicity and Low Cost – uses a pair of twisted wires and does not need and complex devices used as transceivers
- Fully Centralised – enables single point of entry to communicate with all submodules, providing great understanding of data logged within each element of the architecture
- Robust – it has a good resistance to potential EMI within working environment
- Efficient – it is capable to prioritise data collection based on ID number requested
- Easy to Deploy – standard CANBUS has been in use since 1991 and nowadays its application is widely used, especially in car industry

7.2.3 Message Queuing Telemetry Transport (MQTT)

MQTT (Message Queuing Telemetry Transport) is a simple protocol to establish a communication between several devices. It utilises low bandwidth making it optimal solution for many simple Internet of Things (IoT) applications [157]. The protocol allows user either to remotely control devices or to read data and publish them.

MQTT may use Publish option to send commands to selected receiver. The other option to communicate is to Subscribe. As such, receiving device collects messages directly each time the subscribed channel published a message. Messages exchanged between devices involve either commands or data.

MQTT may use home internet network (Wifi, Zigbee) or cellular networks such as 3G, 4G or LoRa to exchange data between machines [158].

7.2.4 Open Charge Point Protocol (OCPP)

OCPP is a global communication protocol created by E-Laad Foundation. It is a standard established to provide communication between charging station as well as EV charging fleet operator. Data exchanged is essential for billing, maintenance and monitoring purposes [159].

The main reason why OCPP was introduced is to provide easy way for adoption of new charging units into existing fleet of chargers. Similarly, operators can benefit from standardised communication protocol. As such, they are able to choose between a wide range of charging solutions available on the market, knowing that each model can be integrated into existing software and hardware infrastructure without any technical difficulties.

OCPP is mainly used by EV charging systems producers who are required to standardise their products before selling them to end customer. Another group of “market players” utilising OCPP benefits are Charging Station Management Systems (CSMS) developers deploying software for fleets of EVs. As a result, they can easily adapt new charging systems into their existing solutions. The last group of users utilising OCPP are Charge Point Operators (CPOs) maintaining customers relationship with their customers.

7.3 Hardware to Control MPC

The following section of this chapter provides comparison between Field Programmable Gate Arrays (FPGA) and Digital Signal Processing (DSP). These two architectures show capabilities to implement control structure for the MPC. Understanding of how they perform while executing complex commands is crucial to determine which device is optimal for further design of the system.

7.3.1 Digital Signal Processing (DSP)

Digital Signal Processing is a method to represent signals using sequence of numbers or data points and processing them to obtain appropriate control functionality. Signals typically are comprised of measured physical parameters which are therefore used for further processing to produce desired outputs.

DSPs rely on Analogue and Digital processing section before the measurement is taken. At this stage, basic signal processing takes place typically by using buffers and filters.

Digital section deals with processing of discrete signals and provides outputs required to satisfy user control demands. The overall concept of data processing using DSP is presented in the block diagram in Figure 57 below.

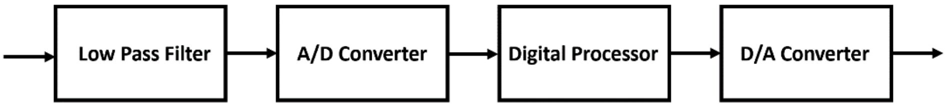


Figure 57 Block Diagram of a DSP System [160]

As presented in Figure 57, Digital Processor providing all essential data conversion specified by the user determines output signal which is therefore feeding D/A Converter providing appropriate control signals within the circuit.

Some of the main advantages of using DSPs involve system flexibility. By analysing digital signals, it is possible to perform complicated digital signal analysis in a relatively simple way. DSPs also allows user to simply modify control of the processor with modest modifications of the software.

DSPs also provide great data storage capacity since devices used to provide memory for digital data are become cheaper and more compact in order to maintain larger amounts of data for further processing.

Finally, cost of using DSPs is low making it affordable solution for a wide range of application in various sectors.

The main disadvantages of implementation of DSPs are associated with relatively high-power consumption required to provide desired functionality as well as requirement to understand basics of digital data processing to implement desired functionalities.

7.3.2 Field Programmable Gate Array (FPGA)

Another potential solution used to implement control strategies for MPC could involve use of FPGA. Such systems are comprised of a wide range of logic gates operating simultaneously in parallel using reprogrammable semiconductors [161], [162]. FPGA users can specify desired operations using available flip flops, look-up tables and multiplexers in order to obtain certain control functionality.

FPGAs have some advantage over other solutions for control of electronic devices. They primarily execute numerous functions simultaneously instead of following certain code based on series of commands. Such parallelisation provides rapid accomplishment of numerous tasks simultaneously. This is particularly important while handling wide number of data sets. These features of FPGA allow sorting and filtering great amount of input data in a short period of time bringing benefits for various applications.

Another advantage of FPGAs is their robustness as well as overall lifecycle duration. These features make FPGA technology appropriate in various industries where resilient operation is fundamental. FPGAs are currently used in defence sector, aerospace, energy and more [163].

FPGAs are also frequently chosen technologies used to prototype new technologies. Their design provides simple reconfiguration features allowing engineers to validate technical solutions as well as adjust them in order to tune the system respecting obtained results. These features allow user to minimise time required to prepare technology to meet the market requirements.

7.4 Comparison between DSP and FPGA for MPC

Section 7.4 presents a preliminary assessment to verify capabilities for DSP and FPGA while being used for one of the selected MPC topologies. The valuation is based on a high-level review of TMS329F283335 (DSP) and XC7A100T (FPGA) boards primarily considering capabilities of their peripherals. These two particular types of controllers are specially used in the power electronics industry. More detailed analysis is recommended once appropriate control structure is developed at further steps of project implementation.

In order to verify feasibility of selected boards, a single configuration from Chapter 6 was chosen as a reference. It was assumed that the most appropriate topology for further analysis is Two-Stage Cascaded AC/DC Converter introduced in Figure 40. Such configuration applies Power Factor Correction (PFC) and Phase-Shifted Full Bridge (PSFB) sections making relatively complex control architecture of the system. This requires an appropriate management of multiple switches simultaneously. Duty cycle adjustment is required to be regulated according to measurements provided by Analogue-to-Digital converters.

In order to assess preliminary use of TMS329F283335 and XC7A100T boards it is required to count the number of ADC and PWM ports supported by each system. TMS329F283335 datasheet reveals that DSP has 16 ADC channels with 12-bit resolution and up to 18 PWM pins [Reference]. For FPGA, a typical method to measure data takes place using an external ADC converter which therefore sends measurements to the main board in a digital format. As a result, the number of ADC pins depends on external devices.

Based on the initial assessment of the analysed power converter, it is assumed that in order to manage it appropriately, hardware requires a minimum of 12 PWM ports, one for each switching device in the design (see Figure 40). Simultaneously, number of ports required to sample voltages and currents is equal to 13 (eight currents and five voltages). These functionalities can be provided by TMS329F283335 which has already been used to support Two-Stage PFC and PSFB converter in the laboratory experiment. FPGAs as an alternative to DSP also show great capabilities to control PWM ports. These systems have fully programmable

Input/Output ports giving users great capabilities to specify switching frequency and duty cycle for each one of them, making FPGA also a suitable structure managing a wide range of switching devices [164]. Voltage and current measurements used by FPGAs are completed using external ADC converter sending data to the main board in a digital format. As a result, the number of ADC pins depends on external devices communicating with the XC7A100T.

Although configuration analysed in this section could be managed by both DSP and FPGA boards, other converter architectures could impose certain limitations on proposed boards. This is evident while considering converters operating at high switching frequencies such as LLC resonant systems where high computational speed of the processing unit is crucial. Lack of a rapid control system can cause high voltage ripple and poor dynamic performance of the power converter. In such cases, FPGA could be a preferred option managing multiple switching devices simultaneously, primarily due to switching frequency being up to six times higher than for DSPs [165]. Furthermore, operational bandwidth of an FPGA is estimated to be seven times higher than while using DSP. The downside of using FPGA may result from limited mathematical complexity supporting the control system.

Further assessment of FPGA vs DSP for MPC requires greater understanding of converter topologies and functionalities in order to define optimal control structure.

7.5 Conclusion

Chapter 7 of the report focuses on a high-level review of communication technologies as well as control infrastructure for future design of MPC.

First part of the chapter introduces communication technology which currently supports various appliances selected for MPC design in the case studies from Chapter 3. Fundamental features of each method are therefore listed in sections 7.2.1 - 7.2.4.

Section 7.4 provides basic comparison between control infrastructure which has potential to introduce appropriate functionality of the MPC. In order to maintain optimal operation, either DSP or FPGA boards are proposed. Each of them presents some benefits while being deployed to support complex power electronics circuits for the MPC. Further investigation of appropriate control infrastructure is expected once final MPC topologies for further assessment are selected.

8 Conclusions

Research outcomes highlighted in this document give a solid understanding of preliminary studies produced in the first phase of iPLUG Multiport Converter Project. Initial work delivered to date has been accomplished under the leadership of the University of Strathclyde researchers who managed work load between all consortium members under Work Package 1. Activities completed required contribution from each institution involved in studies, based on individual expertise. Research reviews were typically presented during biweekly iPLUG internal meetings when each team member conducting studies would have a chance to discuss the main outcomes, challenges and opportunities of specific project task.

Outcomes generated so far under WP1 give preliminary review of MPC applications, use cases and functionalities. To achieve these goals, all initial research activities were divided between two groups. First, considering practical applications of MPC with potential to improve performance of the distribution network, household power management or off-grid microgrid performance. Second, looking at highly technical aspects of converters' topologies to recognise crucial benefits that MPC can introduce over more conventional approaches solving challenges imposed by the existing electrical infrastructure. All research activities completed by the team result in development of significant amount of material supporting future work for the iPLUG team members.

Deliverable 1.1 document starts with the elaboration on definition of MPCs proposed by the consortium members. In order to clearly define it, preliminary literature review had been conducted. Fundamental outcomes give understanding of set of features used to characterise MPCs giving a solid understanding of basic aspects common for all of them.

Chapter 3 gives introduction to potential scenarios where MPC could significantly improve operation of the system. All cases identified were classified under one of three groups. These include Enhanced Soft Open Points with Integration of Renewables, Household Applications and Interconnected Communities. The first group provides understanding of locations where MPC could integrate two or more distribution networks improving their performance and providing additional renewable capacity in the system. Second group reveals cases where MPC has potential to integrate small scale PV generation, EV, battery with the local distribution network. The third group of study cases introduces scenarios where MPC shows potential to integrate wide range of appliances in off-grid environment where wide range of generation sources, storage devices and LV interconnectors could be used. Out of all scenarios proposed, several with the greatest importance and data availability is expected to be used as inputs to Task 1.3 within WP1 as well as to WP2 and WP3.

The subsequent chapter of the report gives a detailed understanding of standards and regulations required to follow while designing MPC. To accomplish this task, detailed review of grid codes and safety requirements was performed. The review provides fundamental understanding of minimum operating conditions to compile with power system requirements and system dynamics to support smooth connection of MPC with the existing power networks.

Chapter 5 focuses on definition of Key Performance Indicators that are selected to quantify benefits of MPC over other methods to tackle certain technical challenges. These are divided between Network and Converter KPIs and are expected to be used in WP1, WP2 and WP3 for further assessment. Network KPIs are to be measured with a support of load flow analysis whereas Converter KPIs primarily depend on technical design and configuration of the MPC.

The penultimate chapter of Deliverable 1.1 summarises a wide range of MPC configurations. These are classified in several groups as indicated in Section 2.1. The literature review uses a Pugh Matrix scoring approach to firstly outline the features that are particularly important for different iPLUG scenarios before allocating scores to the reviewed topologies in terms of these features. Several isolated (modular multi-active bridge) and partially-isolated (two-stage AC-DC-DC MPC, cascaded two-stage PFC and PSFB, two-stage T-type battery charger, dual 3-phase active bridge, and multilevel UPQC) topologies exhibit particular suitability for the iPLUG scenarios. These topologies perform well due to their flexibility to be configured for the given applications along with their provision of desirable characteristics including isolation, voltage gain, modularity, scalability, and low relative numbers of active and passive devices. Further research regarding the specific characteristics relating to the KPIs in Section 5 and the optimisation of device number for the most cost-effective operation at different voltage levels is required to further develop these solutions.

Chapter 7 indicates the main communication and control features to be considered while designing the MPC. First sections of the chapter give summary of appliances which are most likely going to be connected to selected MPC ports as well as their communication standards which are expected to be supported by the future design of MPC. The final sections of the chapter give understanding of the main features provided by DSPs and FPGAs. The summary highlights the main differences between both in order to optimise and simplify potential development of the MPC.

Studies conducted to date fully satisfy requirements anticipated before initialisation of the project. All challenges associated with data collection, case studies and topologies definition have been overcome and material produced gives sufficient background to start upcoming research activities produced by the consortium members.

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10 Appendices

10.1 Grid code requirements

Table 25 Voltage operating condition requirements

			Inner range				Outer range			
GC	**Specific application**	**Base (V)**	**Min (%)**	**Min delay (s)**	**Max (%)**	**Max delay (s)**	**Min (%)**	**Min delay (s)**	**Max (%)**	**Max delay (s)**
AS 4777.2		230	-22	2.00	13	2.00			15	
"		240	-22	2.00	13	2.00				
NZS 4777.2		230	-22	2.00	9	2.00				
BDEW		230	-20	1.50 to 2.40	20	0.10	-55	0.30		
ARCONEL 003			-10	1.00	10	1.00				
VDE-AR-N 4105		230	-20	0.10	10	0.10			15	0.10
CLC/TS 50549-1		≤1000	-15		20				30	
CEI 0-21		230	-15	0.40	10	603.00	-60	0.20	15	0.20
CEI 0-16			-10		10		-15		10	
IEC/IEEE/PAS 63547	≤30 kW	120 to 600	-12	2.00	10	1.00	-50	0.16	20	0.16
"	>30 kW	120 to 600	-12	2.00	10	1.00	-50	0.16	20	0.16
IEEE 929		120	-12	2.00	10	2.00	-50	0.10	37	0.03
IEEE 1547	Essential stability	120 to 600	-30	2.00	10	2.00	-55	0.16	20	0.16

"	Extended stability	120 to 600	-30	10.00	10	2.00	-55	0.16	20	0.16
"	Stability with high DERs	120 to 600	-12	21.00	10	13.00	-50	2.00	20	0.16
GAZETTE OF INDIA PART 3 SEC.4		230	-20	2.00	10	2.00				
EN 50438		230	-15	1.50	10	0.20			15	3.00
G59		230	-18	2.48	17	0.98	-22	0.48	21	0.48
G83		230	-13	2.50	14	1.00	-20	0.50	19	0.50
GB-T 19964		220	-10		10	10.00			20	0.50
Rule 21			-12	2.00	10	1.00	-40	1.00	20	0.16
IEC 61727			-15	2.00	10	2.00	-50	0.10	35	0.05
ANSCI C84.1		120	-5		5		-8		6	
"		600	-3		5					
IEC 61000-2-2			-10		10					
EN 50160			-10		10		-15		10	
D4 2.3	Anything without internal combustion engine		-30	0.70			-30	0.15		
DK 3.3.1	≤125 kW		-15	10.00 to 60.00	10	60.00	-20	0.05 to 1.50	15	0.20

Table 26 Frequency operating conditions

			Inner range				Outer range			
GC	**Specific application**	**Base (V)**	**Min (%)**	**Min delay (s)**	**Max (%)**	**Max delay (s)**	**Min (%)**	**Min delay (s)**	**Max (%)**	**Max delay (s)**
AS 4777.2		50	-6.0	2.00	4.0	2.00				
NZS 4777.2		50	-6.0	2.00	4.0	2.00				
BDEW		50	-5.0	0.10	4.0	0.10				
ARCONEL 003		60	-0.8		0.8					
VDE-AR-N 4105		50	-5.0	0.10	3.0	0.10				
CLC/TS 50549-1		50	-3.0		3.0		-5.0			
CLC/TS 50549-1		50	-3.0		3.0		-5.0			
CEI 0-21		50	-1.0	0.10	0.4	0.10	-5.0	0.10 or 4.00	3.0	0.10 or 1.00
CEI 0-16		50	-0.2		0.2		-5.0		3.0	
IEC/IEEE/PAS 63547	≤30 kW	60	-1.2	0.16	0.8	0.16				
"	>30 kW	60	-2.7	0.16 to 300	0.8	0.16	-5.0	0.16		
IEEE 929		60	-1.2	0.10	0.8	0.10				
IEEE 1547	Essential stability	60	-2.5	300.00	2.0	300.00	-5.8	0.16	3.3	0.16
"	Extended stability	60	-2.5	300.00	2.0	300.00	-5.8	0.16	3.3	0.16
"	Stability with high DERs	60	-2.5	300.00	2.0	300.00	-5.8	0.16	3.3	0.16
GAZETTE OF INDIA PART 3 SEC.4		50	-5.0	0.20	1.0	0.20				
EN 50438		50	-5.0	0.50	4.0	0.50				

G59		50	-5.0	20.00	3	90.00	-6.0	0.50	4.0	0.50
GB-T 20046		50	-1.0	2.00	1.0	2.00				
UNE/EN/IEC 62109		50	-6.0		4.0					
UL 1741		60	-1.2	0.10	0.8	0.10				
Rule 21		60	-0.8	2.00	0.8	2.00	-5.0	0.16	3.3	0.16
IEC 61727		60	-1.7	0.20	1.7	0.20				
DK 3.3.1	≤125 kW	50	-5.0	0.20	3.0	0.20				

Table 27 Power factor capability requirements

GC	Specific application	Relevant power level	Lead PF limit	Lag PF limit	Notes
AS 4777.2		0.25 to 1	0.95	0.95	
BDEW		ANY	0.95	0.95	<10 mins
CLC/TS 50549-1			0.9	0.9	
CEI 0-21			0.9	0.9	
IEEE 929		>0.1	0.85	0.85	
VDE-AR-N 41052	≤13.8kVA		0.95	0.95	<10 mins
"	FAR FROM LOAD CENTRES		0.9	0.95	"
GAZETTE OF INDIA PART 3 SEC.4 ON OR AFTER 2014			0.85	0.95	"
EN 50438		≥0.2	0.9	0.9	
"		<0.2	$Q/P_{n\leq}0.1$	$Q/P_{n\leq}0.1$	

G 59		=1	0.95	0.95	
G 83		=1	0.95	0.95	
GB-T 199644		<1	0.95	0.95	
GB-T 20046		≤0.5		0.9	
IEEE 1547		≥0.2	Q/Pn≤ 0.44	Q/Pn≤ 0.25	
"		<0.2	Q/Pn≤ 0.44	Q/Pn≤ 0.44	
IEEE 1547.9			0.9	0.9	
Rule 21	≤15 KVA		0.9	0.9	
"	>15 KVA		0.85	0.85	
DK 3.3.1	CATEGORY A	≤0.9	0.9	0.9	Design freedom for PF range where 0.9<p≤1

Table 28 Voltage ride-through requirements, where the voltage and time points e.g. LV1 and Lt1 are depicted in Figure 21

	LVRT				HVRT				
GC	**LV1 (PU)**	**Lt1 (s)**	**LV2 (PU)**	**Lt2 (s)**	**HV1 (PU)**	**Ht1 (s)**	**HV2 (PU)**	**Ht2 (s)**	**Notes**
CLC/TS 50549-1	0.05	0.2	0.85	1.9	1.2	0.1	1.15	1	
EN 50438	0.05	0.25	0.85	3	1.25	0.1	1.2	5	
IEEE 1547									Depend on the provision of dynamic support
BDEW	0	0.15							Depend on fault type and agreement with SO
CEI 0-16	0	0.2	0.85	1.5	1.2	0.1	1.15	0.5	
CEI 0-21	0								

GB-T 19954	0								
DK 3.2.2	0.1	0.4	0.85	1.5					
DK 3.3.1									
PR MTR	0	0.6	0.85	3	1.4	1	1.25	3	
CLC/TS 50549-1	0	0.15							
EN 50438	0	0.2	0.85	1.5	1.2	0.1	1.15	0.5	

Table 29 Harmonic requirements defined in percentage of distortion

	GC	**AS 4777.2, IEC 61727**	**IEC/IEEE/PAS 36547, IEEE 929, UL 1741, IEEEE 1547 + Rule 21**	**GB-T 20046**	**DK 3.3.1**	
Current harmonic distortion (%)	**3**	4			3.4	
	5	4			3.8	
	7	4			2.5	
	9		4	4	0.5	
	11	2			1.2	
	13	2			0.7	
	15		2	2	0.35	
	17 to **19**	1				
	21		1.5	1.5		
	23 to **33**	0.6	0.6	0.6		
	35		0.3			
	2	1	1	1	0.5	
	4	1	1	1	0.5	

	6	1	1	1	1	
	8	1	1	1	0.8	
	10		0.5		0.6	
	12		0.375		0.5	
	14 to 16		0.375			
	18 to 22	0.5	0.15	0.5		
	24 to 32		0.075			
	34		0.15			
	36		0.075			
	THD (%)	5	5	5	4.4	

Table 30 Harmonic requirements defined in A/MVA of distortion

	GC	**BDEW**			**VDE-AR-N 4105**
	Voltage level	**10kV**	**20 kV**	**30 kV**	
Current harmonic distortion (A/MVA)	3				3
	5	0.058	0.029	0.019	1.5
	7	0.082	0.041	0.027	1
	9				0.7
	11	0.052	0.026	0.017	0.5
	13	0.038	0.019	0.013	0.4
	15				
	17	0.022	0.011	0.07	0.3
	19	0.018	0.009	0.006	0.25

	21				
	23	0.012	0.006	0.004	0.2
	25	0.01	0.005	0.003	0.15
	25<v<40	0.01*25/v	0.005*25/v	0.003*25/v	0.15-25/v
	even harmonics	0.06/v	0.03/v	0.02/v	1.5/v
	mu<40	0.06/mu	0.03/mu	0.02/mu	1.5/v
	40<mu,v<42	0.18/mu	0.09/mu	0.06/mu	
	42<v,mu<178	0.18/mu	0.09/mu	0.06/mu	4.5/v

10.2 Review of multiport power converter topologies

Table 31 Key features of reviewed MPC topologies. The isolation class is described in Figure 1.

Reference	Topology name	Application (e.g. Solar + ESS)	Power	Voltage		Isolation class	Cell interconnection	Voltage decoupling	Resonance	Modularity	Scalability	Number of ports				Number of switches	Number of passive devices
				Peak port	Max gain							Total	Bidirectional	AC	DC		
[102]	Three-port bidirectional converter	Battery storage, AC load, fuel cell	500 W	400 V	8.33	C1	Independent	Full	None	N	N	3	2	0	3	24	11
[103]	Three-port series resonant DC MPC	Battery storage, AC load, RES	500 W	200 V	16.66	C1	Independent	Full	Single	N	N	3	3	0	3	24	11

[104]	Triple-active bridge	Battery storage, fuel cell, AC load	1000 W	220 V	11.00	C1	Independent	Full	None	N	N	3	3	0	3	24	13
[105]	Asymmetric quad-active bridge	Modular smart transformer	20 kW	800 V	0.88	C1	Independent	None	None	Y	N	N	N	0	N	(2*N-1)*24	(2*N+2)*3
[106]	Symmetric quad-active bridge	Solid state transformer, DER, battery storage, AC load	250 W	48 V	1.00	C1	Independent	Full	None	Y	Y	N	N	0	N	N*8	3*N+1
[107]	Modular MF-based	Solar, ESS, loads, AC	Flexible	Flexible	-	C1	Series	Full	Single	Y	Y	3	3	2	1	Variable	Variable

	converter	grid interconnection														
[108]	Modular multi-active bridge	No application in particular	3200 W	400 V	16.66	C2	Parallel	Full	Multi	Y	Y	N	N	0	N	8*N	5*N
[109]	CLL resonant MPC	No application in particular	1000 W	200 V	5.00	C2	Independent	Full	Single	Y	Y	N	N-1	0	N	4+4*N	(N-1)*5+1
[5]	Dual-transformer asymmetrical TAB	No application in particular	1000 W	100 V	5.00	C2	Independent	Full	None	Y	N	3	2	0	3	28	9
[110]	Modular multi-active bridge	Balanced and unbalanced power	300 W	50 V	1.00	C2	Parallel	Full	None	Y	Y	N	N	0	N	8*N	5*N

		from ports															
[111]	Symmetric dual-transformer TAB	No application in particular	1000 W	100 V	-	C2	Independent	Full	None	N	N	3	2	0	3	24	7
[112]	Modular multi-active bridge	No application in particular	-	500 V	1.20	C2	Parallel	Full	Multi	Y	Y	N	N	0	N	8*N	3*N+1
[113]	Modular DAB-based converter	Solar, ESS, loads, AC grid interconnection	Flexible	Flexible		C2	Series cells, parallel DC port	Full	Multi	Y	Y	3	3	2	1	Variable	Variable
[4]	Cascaded boost converter	Solar, ESS, AC load	200-1200 W	100 V	1.67	C3	Parallel	None	None	N	N	3	1	0	3	7	7

[114]	Magnetically coupled DC MPC	SST to interface solar, ESS, DC grid	200 W	380 V	7.92	C3	Parallel	Full	Single	N	N	3	1	0	3	10	16
[115]	Reconfigurable inverter	Solar, ESS, AC grid	3000 W	200 V	2.22	C4	Independent	None	None	N	N	3	2	1	2	23	14
[116]	Boost derived hybrid converter	DC source, AC and DC loads	-	127 V	2.64	C4	Parallel	Partial	None	N	N	3	1	1	2	9	4
[117]	Modular half-bridge cells based converter	Solar, ESS, AC loads/grid interconnection	Flexible	Flexible	-	C4	Series	Full	None	Y	Y	3	3	2	1	Variable	Variable

[6]	Buck-boost isolated three-port DC converter	PV, battery storage, AC load	250 W	80 V	6.25	C5	Independent	Full	None	N	N	3	1	0	3	11	8
[118]	Two-stage AC-DC-DC MPC	Battery charger	3 kW	660 V	2.20	C5	Independent	Full	None	Y	Y	N	N	1	N-1	20+8*(N-2)	6+3*(N-2)
[119]	Cascaded two-stage PFC and PSFB	Aircarft applications	6 kW	650	23.20	C5	Independent	Full	None	Y	Y	N	N	1	N-1	20+4*(N-2)	7+4*(N-2)
[120]	Two-stage T-type battery charger	Battery charger	3.5 kW	650	27.00	C5	Independent	Full	None	Y	Y	N	N-1	1	N-1	20+(N-1)*12	7+(N-1)*6

[121]	Multilevel UPQC	No application in particular	3 MVA	32.4 kV	-	C5	Series	Full	None	Y	Y	N	N	2	N-2	(N-2)*16	(N-2)*4
[122]	Dual three-phase active Bridge	Quad-port soft open point	8 kW	800 V	2.00	C6	Independent	Full	None	Y	Y	N	N	N/2	N/2	N*6	5*N+3
[123]	Two-switch isolated MPC	Power supply	1 kW	375 V	4.90	C6	Independent	Full	Single	N	N	3	3	1	2	12	14

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