



# DC POWER

## D3.2 System Architecture

June 2024

TH OWL/IFE



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## Document Information

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## EXECUTIVE SUMMARY

This deliverable updates and details the D<sup>3</sup>Bus system concept, which also includes the architecture and preliminary requirement specification as defined in this proposal to take into account the results of D3.1, and developments that have taken place between submission of this proposal and start of the DC-POWER project.

Apart from IFE who leads this task, CEA, AEG, TPE, ARC and ENF contribute with updates/details for their devices or system aspects. SCH contributes with the protection strategy. MPHDE, MPHIT and JSI contribute with updated plans for the realisation of their pilot sites.

A plan for the system architecture of the pilot sites is developed, which is based on the D<sup>3</sup>Bus system concept. This plan covers the requirement specifications and the user needs. It also covers redundancy planning to ensure stable operation despite component or grid faults.



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# 1 Executive Summary

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This first version of the document will be updated in June 2025 and June 2026 to achieve a definitive version.



## 2 Definitions

|      |   |
|------|---|
| AFE  | Active Front-End                                    |
| D    | Deliverable   |
| LSIG | Long time, Short time, Instantaneous & Ground fault |
| OP   | Operating Point                                     |
| PEMS | Power & Energy Management System                    |
| T    | Task  |
| UPS  | Uninterrupted Power Supply                          |
| WP   | Work Package  |



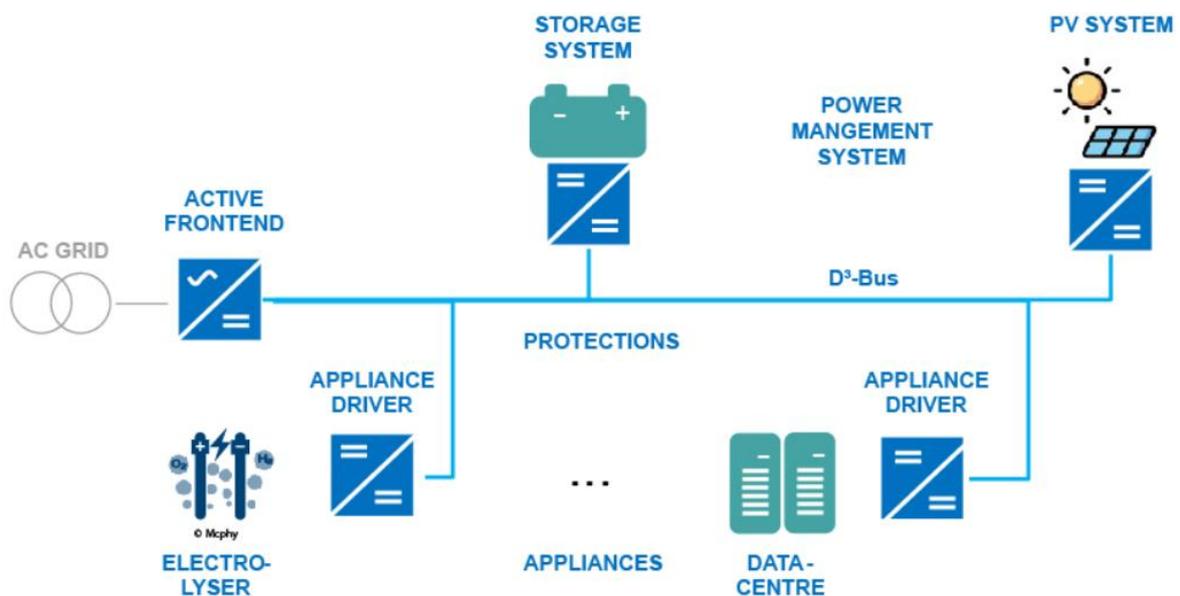
### 3 A medium voltage direct current distribution system

The DC-POWER project proposes a local medium voltage direct current distribution bus architecture—the D3-Bus (for Dual DC Distribution Bus)— for an optimised distribution of power in the Megawatt range. This D3-Bus is envisioned to manage electric power distribution at building/site level, incorporating industrial high-power loads as well as local energy generation and storage. This will be demonstrated in two operational pilots, in a data centre and in an industrial application.

This section gives as an introduction and overview on the system concept and the key components involved, as well as an overview on the pilot systems to be realized.

#### 3.1 System concept

The following diagram outlines the system concept envisaged.



This system concept including the following components :

- The D3-Bus

The D3-Bus (Dual DC Distribution Bus) is a bipolar DC bus operating at  $\pm 1.5$  kV. The DC bus is inherently bidirectional and allows free flow of power between the connected components.

- Active Front-End

The Active Front-End is connected to the medium voltage AC grid and provides power



for the D3-Bus. It also feeds back power to the AC grid when the generated photovoltaic power is not fully used up by the appliances in the DC grid.

- Appliance Driver

The appliances are powered with by the appliance driver, which is a DC/DC converter with galvanic isolation. This driver is powered at 3kV to reduces the currents needed to power MW scale appliances.

- Photovoltaic System

The photovoltaic system provides green power for the appliances. The PV arrays feed each leg of the D3-Bus separately to keep the PV voltages within the low voltage limit of 1.5kV.

- Storage System

The batteries stabilize each leg of the D3-Bus separately to keep the batteries within the low voltage limit of 1.5kV. They can dynamically store and deliver energy depending on whether there is an energy surplus or deficit in the DC grid.

- Power Management System

The power management system assures system stability, manages the battery, and assures that a maximum of PV power is used for the appliances.

- Protections

The protection system assures the security of the D3-Bus in case of severe failures. All subsystems are protected by fast protection switches separately.

The key element of this concept is the use of a medium voltage direct current distribution system which is the D3-Bus. The idea of this D3-Bus is to increase the voltage level with respect to ground to 1,500V (1.5 kV) which is the maximum level still covered by standards and regulations for low voltage systems. To increase power flow, the D3-Bus connects two 1.5 kV nets in series with a grounding between the two. This allows for the connection of both 3 kV and 1.5 kV devices (converters, protections, appliances).



## 3.2 Overview on Pilot 1: Electrolyser

### 3.2.1 Description

The electrolyzer pilot for the DC-Power project will be installed at McPhy's San Miniato facility in Italy. The Italian McPhy team specialize in design and production of electrolyzer stacks, as well as assembly and testing of electrolyzers. The San Miniato site's yearly production rate is up to 300 MW, with its stack testing and analysis capacities having been further extended in 2024. Test benches at the San Miniato location provide flexible technology to verify, characterize and improve electrolyzer stacks of varying capacity and innovation characteristics. For the DC-Power project, a test bench will be equipped with an electrolyzer stack of 1MW nominal capacity and, together with a photovoltaic installation, connected to the DC-Power D3Bus.

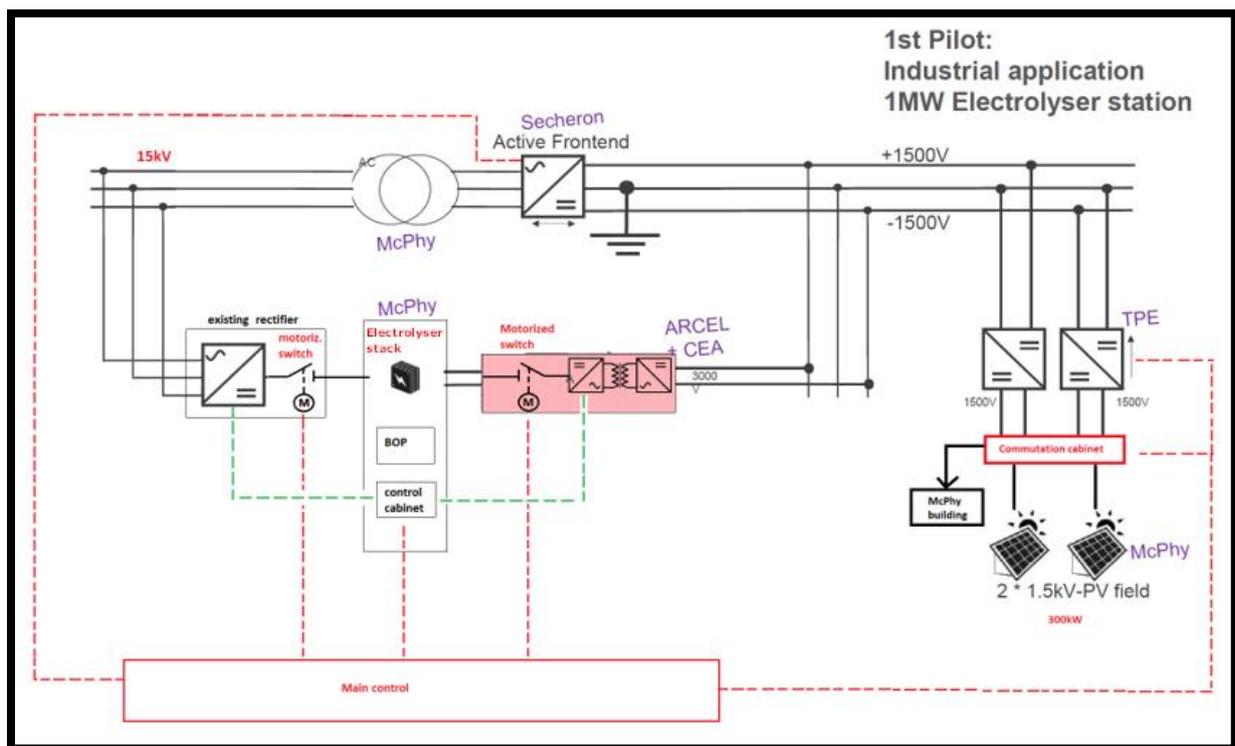


Figure 1: Electrolyser pilot with its relevant connections.



The appliance driver to be developed by the according consortium partners within DC-Power will feed the electrolyser stack within the indicated operating range. The interplay and interfaces between: (i) the electricity supply provided through consortium-developed DC technology, (ii) McPhy standard/fall-back electricity supply from the power grid as well as (iii) the foreseen photovoltaic (PV) modules are planned according to the schematic diagram of

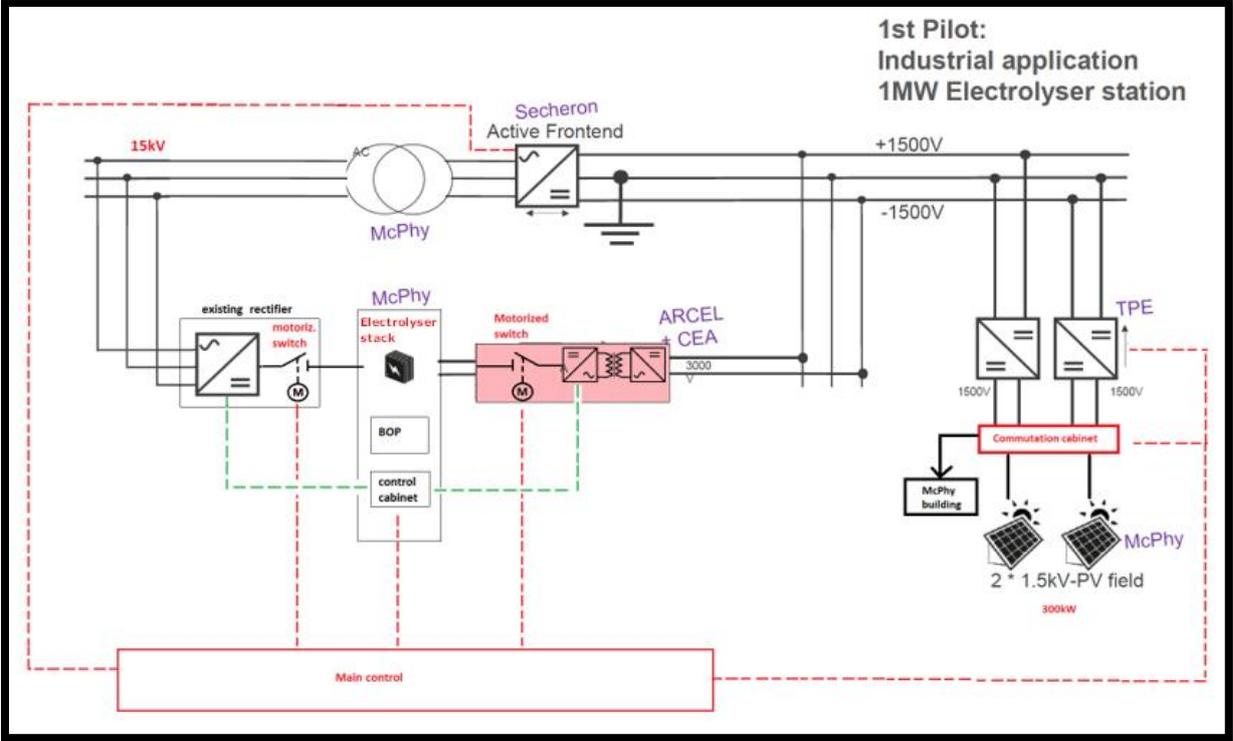


Figure 1.



### 3.2.2 System requirements

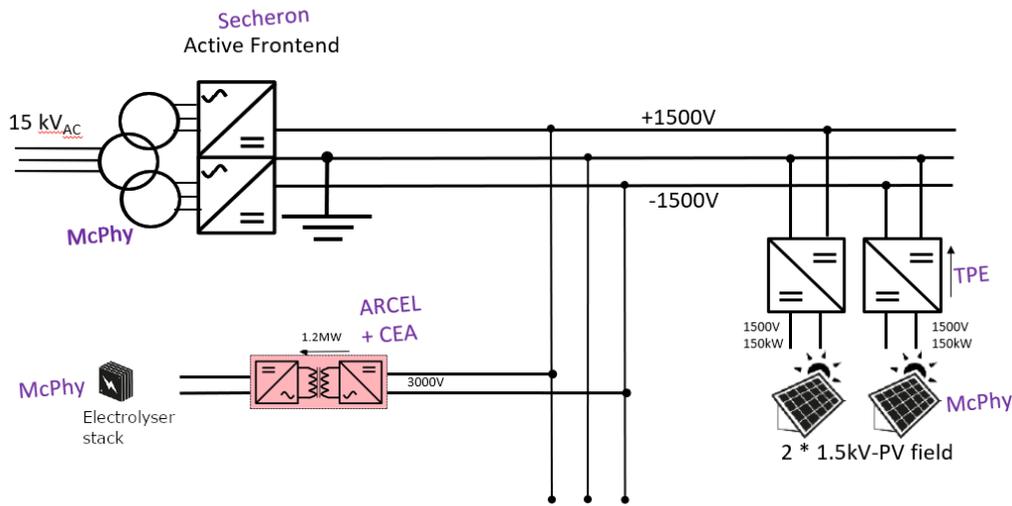


Figure 2: Setup for the electrolyser pilot

The DC Power system should be equipped with a low voltage circuit breaker with LSIG (long time, short time, instantaneous & ground fault) protections.

When the electrolyser input current is less than a defined percentage of its full load current for a defined time period, then the LV switchgear should open as safety operation; this under-current protection should be rated at safety integrity level (SIL) 2 according to IEC 61508.

A DC voltage monitoring system should be installed; that is, the voltage from the DC/DC converter power output DC positive pole to virtual ground and DC power output DC negative pole to virtual ground should be monitored and the difference between them should be measured. If the voltage difference is more than a defined safety value, the system should provide an alarm; and when the difference is equal to or greater than a defined second safety value, the system should trip.

Each compartment provided shall be delivered equipped by the producing consortium partners with a complete cooling system for all sub-components within its scope, including all instrumentation, automatic control systems, alarms, and all components necessary for its own proper operation. The cooling capacity must be sufficient to guarantee operations under operating scenarios of maximum power and high-temperature environmental conditions.

If an air-based cooling system is selected, specify N+1 redundant fans and specific inlet/outlet filters.



### 3.2.3 Earthing of the electrolyser system

The appliance driver powering the electrolyser is provided with a galvanic separation. Therefore, the earthing system of the D3Bus and the electrolyser can be treated independently. Minus point of the stack will be connected to the ground so the system shall be reviewed not to have a DC current leakage to earth. Additional requirements arising from the electrolyser pilot concern the D<sup>3</sup>Bus' earthing system and are discussed in Section 5 of the present document as well as Deliverable D5.4.



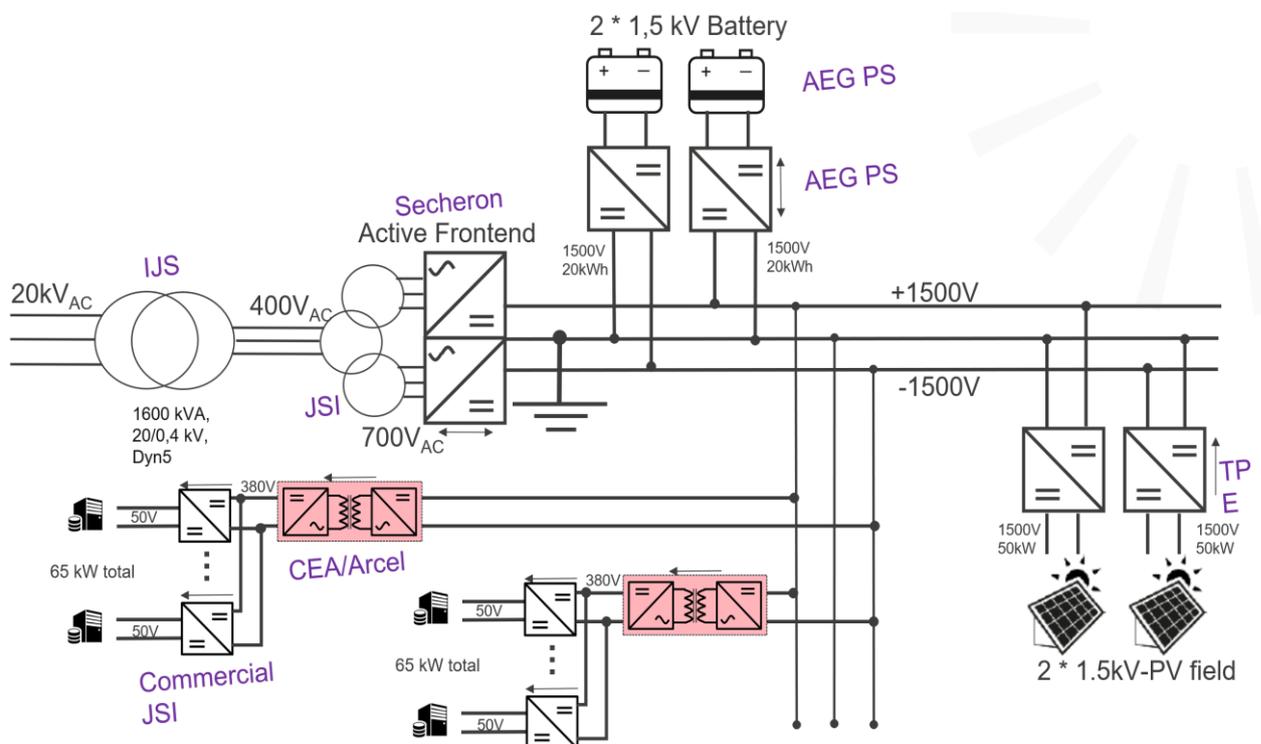
### 3.3 Overview on Pilot 2: Data Centre

#### 3.3.1 Description

For implementing the data centre pilot, six OCP cabinets will be installed, each with a power of 21.6 kW, which will be powered by direct current at 380 V in Tier I mode. Photovoltaic power plant with a capacity of up to 100 kW will be installed on the roof of the data centre.

If a high redundancy level of Tier III is needed for the data centres, it is envisaged to double the D3-Bus system to achieve the redundancy required. For now, no redundant concept is planned.

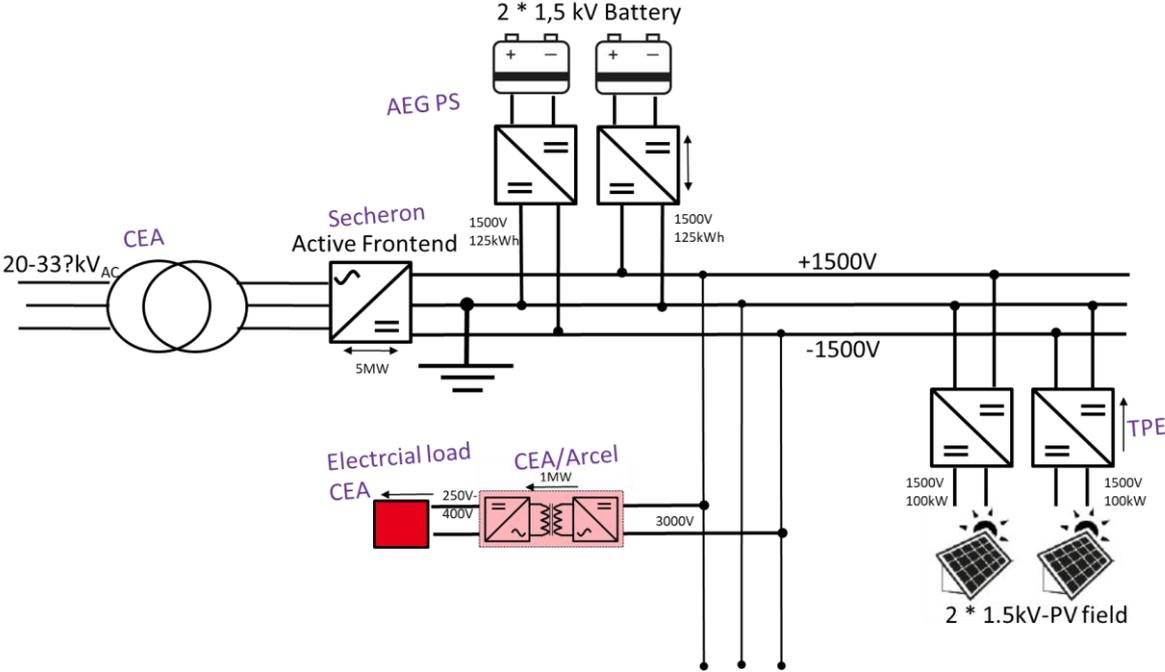
Figure 3: Basic DC power supply schematic of the data centre



### 3.4 Lab test at CEA

The D3-Bus implemented for the first Lab test at CEA will be adapted to cover the bus system characteristics of the Electrolyser and Data centre described before and does not require specific considerations.

Figure 4: Lab test setup at CEA



## 4 Voltage Ranges

The voltage ranges used for the system architecture of the  $\pm 1500$  V D<sup>3</sup>-Bus have to be chosen according to the electrical and technical limits of the devices and applications to be addressed by this concept. For this research project, PV systems, electrolysers and data centres are considered in particular, but not exclusively, as it is intended to be an open concept for other applications.

Further requirements for the choice of voltages are the highest possible energy efficiency and the need for a wide operating range for the use of droop curves for system control. By concept, the operation voltage is not fixed but uses an operation range. However, the operation voltage can be fixed for some simple configurations with only one grid forming device if this benefits the usability or the efficiency.

Both poles of the system are defined symmetrically and controlled separately. For a simpler overview, we will only consider the positive pole between M and L+ in the following sections. The negative pole is defined identically, but with inverted signs.

### 4.1 The voltage basis

We assume a maximum, regulated operating voltage of  $\pm 1500$  V as a basis. This results in a maximum usable voltage difference of 3000 V between the two poles. The lower limit of the operation range should be as high as possible for best energy efficiency.

### 4.2 Limitations of the applications

The limits of the operating values for the applications under consideration are shown below.

#### 4.2.1 PV system

The PV system is divided in two halves, where each half is connected to one pole of the D3-bus system with non-isolating DC/DC converters. The maximum PV system voltage is kept below 1500 V to keep the PV system in the regime of low voltage DC systems.

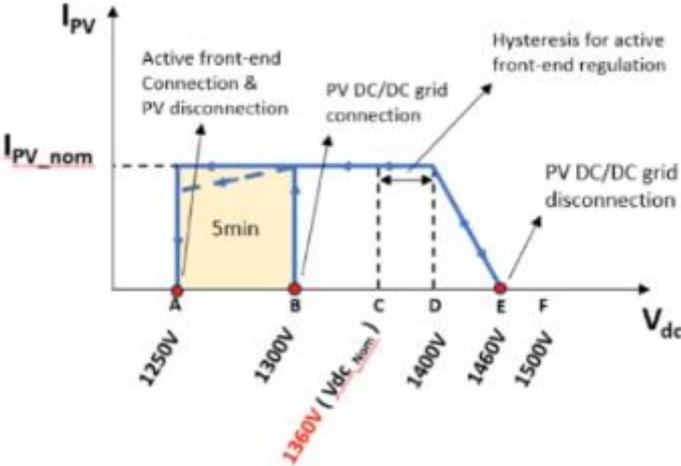
For the PV converter it is the most efficient topology to either use a buck or a boost converter to feed the energy to the D3-bus. This means that the PV voltage, under any circumstance (low temperature, high solar irradiance), must be lower than the actual operation voltage of the pole of the D3-bus at any time to avoid non controllable PV injection on that pole.



The voltage of the PV system increases with the solar irradiance, but also with decreasing temperature. The maximum number of PV modules connected in series of the PV system is determined by the highest solar irradiance and lowest temperature which might occur. The corresponding maximum PV string voltage has been fixed to be **1500 V**.

If the D3-bus voltage is below 1250 V, the PV converter will disconnect for security reasons.

Figure 5: PV operation ranges



#### 4.2.2 Electrolyser

The electrolyser is driven by the appliance driver which is a DC/DC converter powered by the positive and negative pole of the D3-bus. The actual needed maximum voltage of the electrolyser stacks is technically limited well below the bus voltage. So, the needed converter does not interfere with the ranges of the bus voltage.

The appliance driver for the electrolyser is a current source. The setpoint which is send to the appliance driver is the requested DC current. The appliance driver should supply the resulting voltage based on the stack impedance of the electrolyser used for the pilot system.

#### 4.2.3 Data centre

The data centre is driven by several power boxes, which are DC/DC converters powered by the positive and negative pole of the D3-bus and which provide the IT racks with nominal voltages ranging between 240 VDC and 380 VDC. One power box will be able to power at least three standard IT racks totalling 65kW.



The optimal choice is the upper limit of 380 V, as it results in lower current for the same power, thereby reducing losses and enabling the use of conductors with a smaller cross-section. For that reason, the data centre will be operated at 380 V at the input of the rack power supply units<sup>1</sup> (Murata). The holdup time of the power supply units intended for use in the racks is 12 ms. This is an important information for defining the response time of the battery operating as a UPS in case of a failure of the public AC grid.

#### 4.2.4 Other applications

Other useful applications to be considered must be chosen and evaluated from D 3.1 – user needs analysis – and other sources and experiences during the project.

### 4.3 Voltage band system

The voltage band system combines the nominal and abnormal voltage ranges and the desired time domains. The different voltages and times are described below

---

<sup>1</sup> mwocp68-3600-b-rm.ashx (murata.com), mwoces-211-p-c\_a01\_d05.ashx (murata.com)



Figure 6 Voltage band system

| Voltage band | Voltage label | [V]  | DC-POWER Specifications ± 1500 V |                             |                        |                        |            |
|--------------|---------------|------|----------------------------------|-----------------------------|------------------------|------------------------|------------|
|              |               |      | A7                               | A6                          | A5                     | A4                     | A3         |
| B7           | U6            | 2000 | A7                               |                             |                        |                        |            |
| B6           |               |      | A6                               | A7                          |                        |                        |            |
| B5           | U5            | 1760 | A4                               | A5                          | A5                     | A7                     |            |
|              | U4            | 1500 | A3                               | A3                          | A3                     | A4                     | A5         |
| B4           | U3            | 1425 | A3                               | A3                          | A3                     | A3                     | A3         |
|              | U2            | 1300 | A4                               | A4                          | A2                     | A2                     | A2         |
| B2           | U1            | 1170 | A4                               | A1                          |                        |                        |            |
| B1           | -             | 0    |                                  |                             |                        |                        |            |
|              |               |      | S1:                              | S2:                         | S3a:                   | S3b:                   | S4:        |
|              |               |      | $t < 50 \mu s$                   | $50 \mu s \leq t \leq 1 ms$ | $1 ms \leq t \leq 5 s$ | $5 s \leq t \leq 60 s$ | $t > 60 s$ |

#### 4.3.1 Voltage bands (B1-7)

The voltage bands between the defined voltage limits mark the area in which normal operation is possible and where protection devices shall interact.

Table 1: Voltage bands

| Voltage Band | Range [V]   | Description  |
|--------------|-------------|--|
| B7           | 2000 - ∞    | Forbidden band. Damage of devices is very likely   |
| B6           | 1760 - 2000 | Overvoltage protection band. Opening protection devices can cause voltages in this range.  |
| B5           | 1500 - 1760 | Temporary overvoltage band. Insulation and components shall withstand this for up to 5 s. After this time the protection devices open. |
| B4           | 1425 - 1500 | Overvoltage band. Nominal operation up to 60 s.  |
| B3           | 1300 - 1425 | Nominal band. Normal continuous operation.   |
| B2           | 1170 - 1300 | Emergency band. Overload condition, loads have to be reduced. The power sources may switch off to prevent overcurrent.                 |
| B1           | 0 - 1170    | Blackout band. Protection devices open and disconnect. This band is only actively used during pre-charging.                            |



### 4.3.2 Voltage limits (U1-6)

The voltage limits are determined by various conditions. The base voltage is 1500 V as the highest permanently permissible voltage.

Table 2: Voltage limits

| Voltage | Value [V] | Description   |
|---------|-----------|---|
| U6      | 2000      | The highest electrical transient voltage to be expected, e.g., during opening of protection devices.                                    |
| U5      | 1760      | Highest expected overvoltage for up to 5 s.   |
| U4      | 1500      | Upper limit of temporary nominal operation. This value is defined by the upper limit of the low voltage range.                          |
| U3      | 1425      | Upper limit of continuous nominal operation.  |
| U2      | 1300      | Lower limit of continuous nominal operation. This is the lowest possible voltage for efficient use of photovoltaic strings (see 4.2.1). |
| U1      | 1170      | Absolute temporary minimum voltage with 90% of U2.  |

### 4.3.3 Time ranges (S1-4)

The time ranges are based on various requirements and functions in the DC grid and are described in the following table.

Table 3: Time ranges

| Time label | Time range                                | Description  |
|------------|---|--|
| S1         | $t < 50 \mu\text{s}$                      | Transient time range. <sup>2</sup>   |
| S2         | $50 \mu\text{s} \leq t \leq 1 \text{ ms}$ | Fault range. Maximum reaction time of protecting devices.  |
| S3a        | $1 \text{ ms} \leq t \leq 5 \text{ s}$    | Active voltage control range. Basic insulation must withstand voltages higher as the rated voltage up to 5 s. <sup>3</sup> |

<sup>2</sup> According to surge immunity of IEC 61000-4-5.

<sup>3</sup> According to section 5.4.3.2 of IEC 60664-1:2020 for low-voltage supply systems.



|     |  |   |
|-----|--|---|
| S3b | $5 \text{ s} \leq t \leq 60 \text{ s}$ | Active voltage control range. After 60 s steps must have been taken to bring back the voltage to the nominal level. |
| S4  | $t > 60 \text{ s}$                     | Continuous operation  |

#### 4.3.4 Operation states (A1-7)

The operation ranges describe categories of different voltage-time-ranges and what actions must be taken.

Table 4: Operation states

| Operation state | Description   |
|-----------------|---|
| A1              | Blackout state. Devices are shutting down.  |
| A2              | Acute undervoltage. Loads must be decreased. Power supplies may disconnect to prevent overcurrent damage. |
| A3              | Nominal operation state.  |
| A4              | Abnormal state. Devices may reduce power but must continue working.                                       |
| A5              | Devices may switch off to protect themselves.   |
| A6              | Overvoltage protection is active.   |
| A7              | Prohibited state. Damage to devices is likely.  |



## 5 Earthing

This section only provides a brief overview of the different earthing variants, it is finally concluded in Deliverable D5.4. The topic of earthing in DC systems closely parallels that of AC grids, as outlined in IEC 60364-1, chapter 312.2.4. This document describes several system earthing types specific to direct current (DC) systems:

- DC IT System: All active conductors are isolated from earth or are connected to earth through a high impedance, solely for measurement or functional purposes.
- DC TN-S System: One active line conductor or the active midpoint conductor is earthed. The protective earth (PE) conductor is kept separate from this earthed active conductor throughout the system.
- DC TN-C System: The earthed active conductor and the PE conductor are combined throughout the system.
- DC TN-C-S System: The earthed active conductor and the PE conductor are combined in part of the system.

### 5.1 Isolation and Earthing in DC Systems

IEC 60364-1 assumes that the potential of a DC system is isolated from the AC grid and does not cover AC-side earthing. However, IEC TR 63282 distinguishes between two main system types based on conductor configuration:

- Unipolar Systems: Utilize the voltage between two outer conductors (system with L+, L-, and PE)
- Bipolar Systems: Feature a loadable midpoint conductor, providing two voltage levels (system with L+, L-, M, and PE).

The D3-bus is a bipolar system, which can be used bipolar or unipolar.

### 5.2 Comparison of TN-S and TN-C Systems

Both TN-S and TN-C systems have their advantages and disadvantages:

- TN-S Systems: Offer higher safety and better interference suppression but are more expensive and complex to install.
- TN-C Systems: More cost-efficient and easier to install but carry higher risks regarding fault currents and electromagnetic interference.

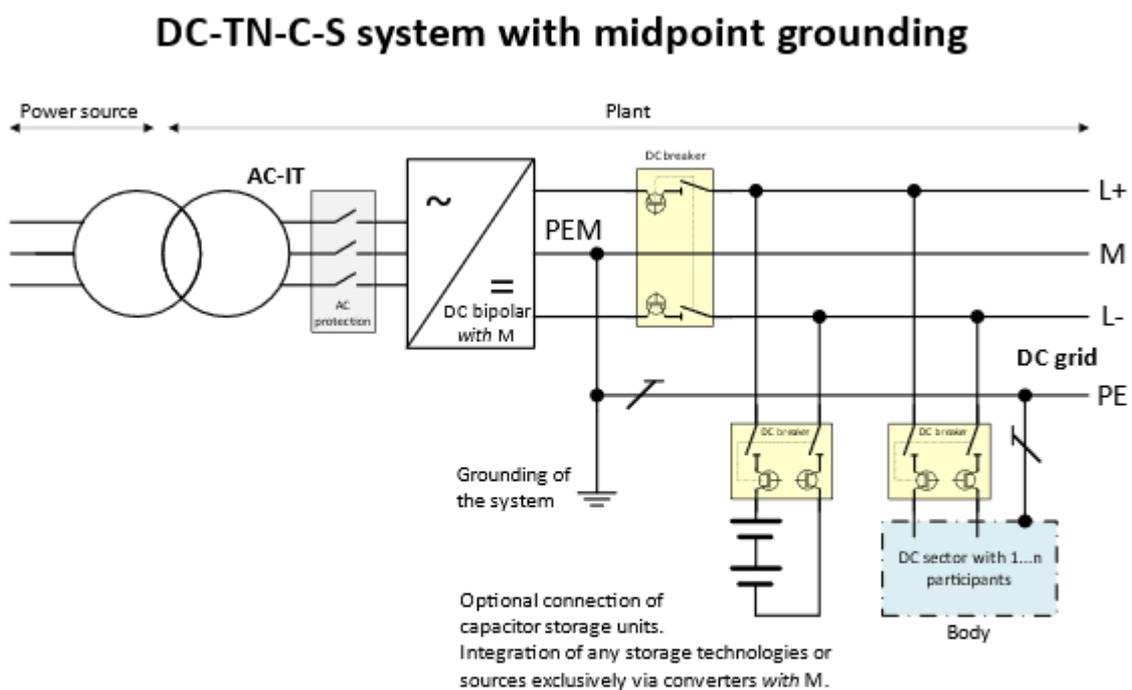


Given these trade-offs, the choice between TN-S and TN-C systems depends on the specific requirements and conditions of the application.

### 5.3 Bipolar TN-S System with Low Impedance Midpoint Earthing

For the DC Power project, we focus on bipolar systems configured as TN-S or TN-C with low impedance centre grounding. Figure 7 illustrates a bipolar TN-S system with low impedance midpoint earthing.

Figure 7: Midpoint grounding in a bipolar DC-TN-C-S system (ODCA 2024, Martin Ehlich / Lenze SE)



The system is grounded centrally via the midpoint (PEM) of the converter(s) connected to sources/storages. The midpoint conductor M can be used to provide a second voltage level, but does not have to be distributed throughout the installation. Fast overcurrent protection in both poles (L+ and L-). Galvanic isolation from grounded AC networks is mandatory.

NOTE 1 Additional grounding of the PE in the installation may be provided (base grounding)

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#### Key Features:

- Grounding Method: The midpoint of the DC voltage is grounded through a low-impedance connection.
- Power Supply: Generates two galvanically isolated DC voltages from the AC grid, connected in series, with their midpoint earthed.



- **Midpoint Conductor:** In industrial applications, it is recommended to avoid using the M conductor as an active conductor to reduce wiring complexity and prevent electrical corrosion. The midpoint conductor is earthed at a single point.

### **Fault Protection and Earthing Challenges**

In DC systems, grounding and protection against fault currents are critical due to the difficulty in detecting and interrupting DC fault currents. Specific considerations include:

- **Intentional Leakage Currents:** Larger DC leakage currents can be intentionally applied to detect insulation faults. These can also result from temporarily activating a symmetrisation device in island operations.
- **Fault Protection:** Required at both poles, similar to AC-side earthing.
- **Single Earthing Point:** The DC system should be earthed at only one point to avoid imbalances and significant DC balancing currents in the earthing system.

This approach aligns with the guidelines provided in IEC TR 63282 and IEC 60364-1.

The grounding scheme of the D3-Bus is further elaborated in Task 5.2 and detailed in deliverable D5.4.



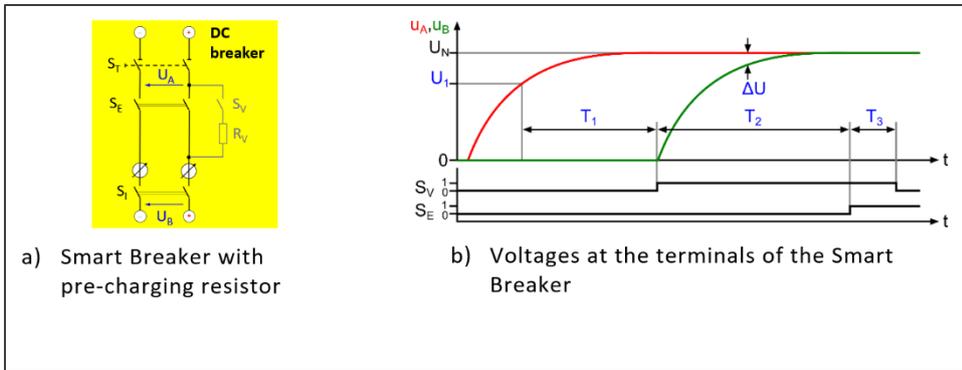
# 6 Pre-charging

The DC Sectors of a DC grid generally contain many capacitances; when uncharged capacitors are connected to a DC voltage, very high inrush currents flow which would cause the protective devices to switch-off without further measures. It therefore is essential to ensure that the inrush current is limited to levels that will not activate protective devices at power-up. This chapter describes the measures for pre-charging capacitances to limit the inrush current. All of them involve monitoring the voltage at the inputs and outputs of pre-charging devices.

Pre-charging takes place sequentially across several levels. It starts with the 1st level, including the power infeed devices and any energy storage systems and thus the unloaded DC grid. All other DC Sectors remain disconnected while this is happening. Following a time delay, the increase in voltage in the DC grid triggers the start of pre-charging of the DC Sectors of the 2nd level (the unloaded first hierarchical level of the DC grid). To enable correct setting of the charging current limitation for the DC Sectors, manufacturers must indicate the device-specific DC link capacitance. If subsectors are connected within a DC sector (constituting a third hierarchical level of the DC grid), they are also pre-charged after a time delay. This staggered pre-charging process should take no more than 10 seconds per level to complete.

The basic principle of sequential pre-charging is shown in Figure 1. Port A of the Smart Breaker is connected to the next-higher hierarchy level, while port B is linked to the next-lower level. The pre-charging process is initiated by the voltage of the next-higher level (shown in red in Figure 1b, measured at port A). When this voltage reaches the value  $U_1$ , even though the next-higher level has not yet finished pre-charging it can be expected that the upstream level to be loadable after the time  $T_1$  has elapsed.

Figure 8: Sequential pre-charging (ODCA, 2024)



After the waiting period  $T_1$ , by which time the upstream hierarchy level must be loadable, pre-charging of the next-lower hierarchical level begins by closing  $S_V$ . The devices connected to



connection B are charged to the voltage at connection A by way of  $R_V$ . If the voltage difference  $\Delta U$  falls below a predetermined value,  $S_E$  is activated, thus bypassing  $R_V$ <sup>4</sup>. Now level B is loadable. The resulting time constant during the charging process must be significantly smaller than  $T_2$  since the charging process must be completed by the end of  $T_2$ . After  $T_3$  has elapsed,  $S_V$  is opened. This breaker should also be capable of closing against the applied line voltage if a fault occurs while pre-charging is ongoing. If there are additional hierarchy levels, the green voltage at port B shown in Figure 8b becomes the new red voltage at the new port A for the next Smart Breaker.

The following values are suggested for the voltage limits and waiting times:

- **Lower voltage threshold** for initiating pre-charging:  $U_1 = 1360V - 10\%$  DC/DC converter we will wait until the DC Bus charging is complete to start charging its own DC capacitor bank. This means AFE has started and is regulating DC bus voltage at 1360V-10%. We can then start the DC/DC converter and generate a DC output voltage.
- **Differential voltage threshold** at the end of pre-charging:  $\Delta U =$  (will be defined by converter manufacturer) This value depends on the resistive bridge that will be used to charge the bus and corresponds to the bus voltage reached before the thyristor or relay is engaged to short-circuit the pre-charge. The exact value will be defined during the design phase, as it depends on the permanent resistive load.
- **Waiting time for the start of pre-charging** by the Smart Breaker:  $T_1 = 5 \text{ s}$
- **Duration of pre-charging:**  $T_2 \leq 4 \text{ s}$
- Switch-off of pre-charging after time  $T_2$ :  $T_3 = 1 \text{ s}$ .

As a constraint,  $T_1 > T_2 + T_3$  must apply to ensure that pre-charging is not initiated for a subsequent level until it has been completed on the preceding level. The time  $T_1$  is determined by the time constant  $\tau$  of the pre-charging process. After a time of  $5 \cdot \tau$  the pre-charging process can be considered complete. It therefore is necessary that  $T_1 > 5 \cdot \tau$ . It is advantageous if the voltage difference  $\Delta U$  can be adjusted on the Smart Breaker to allow for larger values as required by the application.

Depending on the type of power supply and system configuration, it may be necessary to choose a smaller value instead of the suggested voltage threshold of  $U_1 =$  (will be defined by converter manufacturer) so that the supply device can resume supplying power if the DC grid drops below the nominal voltage range (Chapter 4.3).

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<sup>4</sup> Pre-charging via a resistor is just one option, chosen here in Figure 1 as an example.

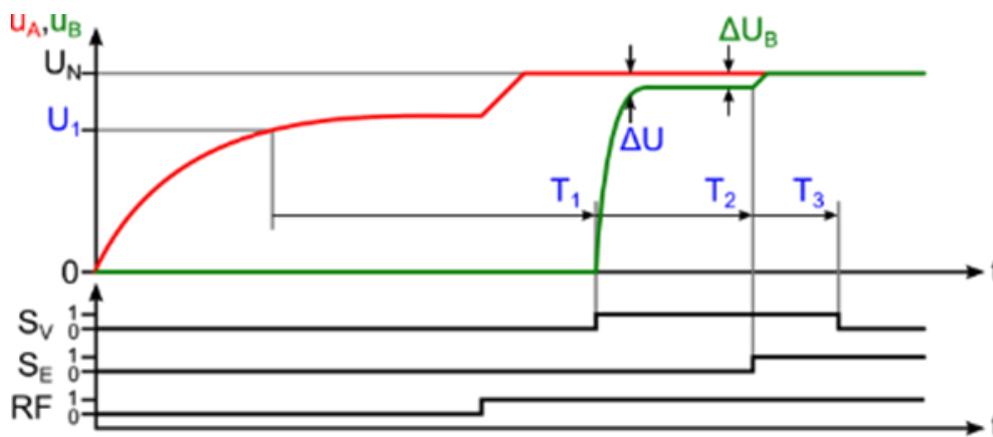


## 6.1 Active Front-End pre-charging

Before starting the first power infeed device (the active front end), the DC grid is discharged and disconnected from the power infeed device ( $S_V$  and  $S_E$  are open as shown in Figure 1). The power infeed device in the 1st level charges itself from the AC grid to the rectified grid voltage and automatically transitions to regulated operation after bypassing the inrush current block. Internal pre-charging to the rectified grid voltage happens before enabling the controller of the power infeed device. The controller release activates regulation of the voltage and current with the predefined droop curves. Then the steady-state voltage of the DC grid becomes established in the power infeed device while the DC grid itself is still voltage-free.

The DC grid (DC grid / 1st hierarchical level) powers up via the Smart Breaker between the first power infeed device and the DC grid. The Smart Breaker monitors the voltage of the power infeed device (shown in red in Figure 9) and initiates pre-charging of the DC grid in response to it. The process is basically as shown in Figure 8. Since no uncharged capacitors are directly connected to the DC grid, charging takes place very quickly (the green voltage curve in Figure 9).

Figure 9: Voltage-time curves during pre-charging of the DC grid (ODCA, 2024)



## 6.2 Soft start for converters connected to DC

Converters connected to the DC grid wait a specified time (see example above) before initiating their own pre-charging process. The converters pre-charge to their nominal secondary side voltage before loads are applied.



6.2.1 Converter Pre-charge Circuit.

Converter pre-charge circuit has the goal of reducing inrush current during converter connection and avoid undervoltage in the DC line and overcurrent and consequently protections tripping. This circuit is mandatory for all converters connected to  $\pm 1500\text{VDC}$  lines.

Two possible solutions for pre-charging process in converters connected to DC line are shown in Figure 10 and Figure 11.

Figure 10: Pre-charge circuit for a converter connected to a DC line, example 1

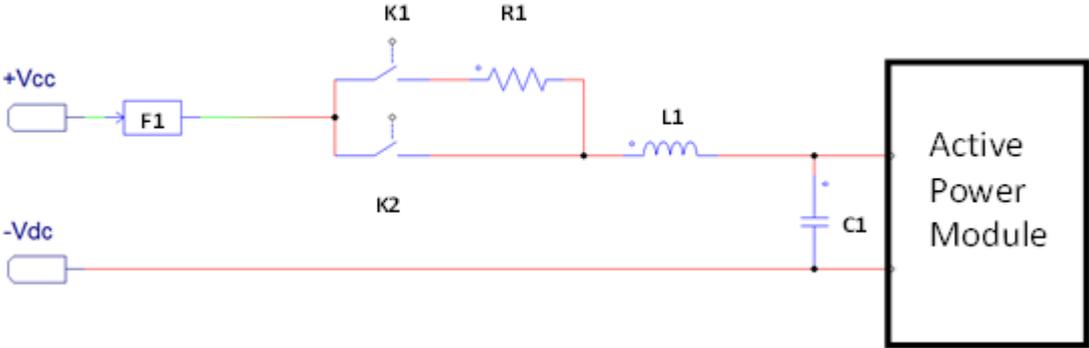
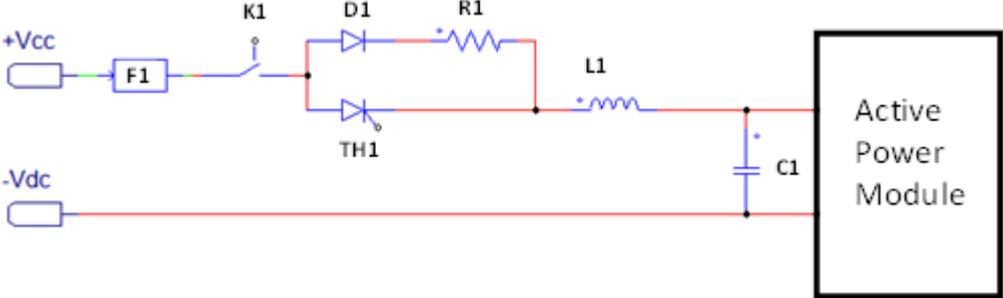


Figure 11: Pre-charge circuit for a converter connected to a DC line, example 2



The circuit of the two figures is formed by following components in Table 5.



Table 5: Components of pre-charge circuits

| Components          | Description.   |
|---------------------|--|
| F1                  | Fuse F1 protects converter against overcurrents and internal short-circuits when other protections fail. Fuses cannot protect semiconductor devices in all scenarios.  |
| K1                  | Contactors are connected in series with resistor R1. K1 and R1 form the pre-charge circuit.  |
| R1                  | It limits the current during pre-charging process.   |
| K2                  | Main contactor. Contactor K2 and fuse F1 can be substituted by a circuit breaker (CB), however the number of connection cycles of circuit breaker are significantly lower, its response is also slower than a fast fuse. However, CB are used for very high currents and high voltages when fuses are not suitable |
| Lin                 | Reactor of the input filter, which is also formed by C1 capacitor bank. This reactor protects the circuit against short term overvoltage, and filters with C1 current harmonics generated by IGBT or SiC Mosfet located in the active power modules.   |
| C1                  | Capacitor bank of input filter. It stores energy at the input of active power module, keeping the DC voltage with less voltage ripple as possible.   |
| Active power module | It includes the rest of semiconductor devices such as IGBT and SiC diodes as well as the rest of components downstream.  |

### Pre-charge operation:

When the DC voltage is present at converter +V<sub>cc</sub> and -V<sub>cc</sub> the contactor K1 is closed and the voltage starts to increase, the current demanded from the grid is limited from resistor R1. The



voltage at capacitor bank C1 starts to increase and current reduces as it is shown in Figure 10.

When voltage has reached about 90%-100% of its final value the main contactor K2 closes. Contactor K1 opens after few seconds of closing K2. This is not a mandatory manoeuvre. Recharging process lasts from several hundreds of milliseconds to several seconds. See figure 2. The inrush current is limited by resistance R1.

Figure 12: Example voltage and current evolution during pre-charge circuit operation of Figure 10

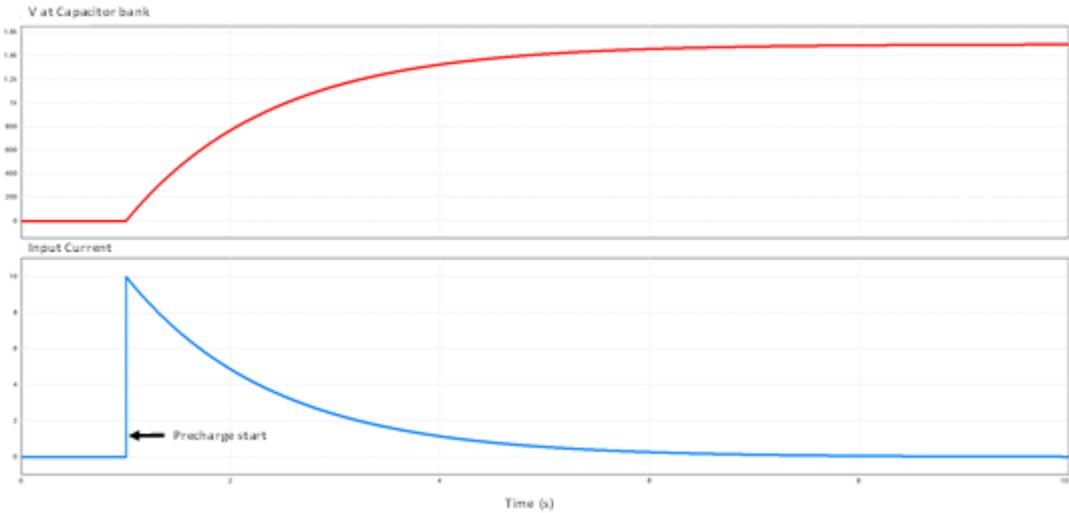


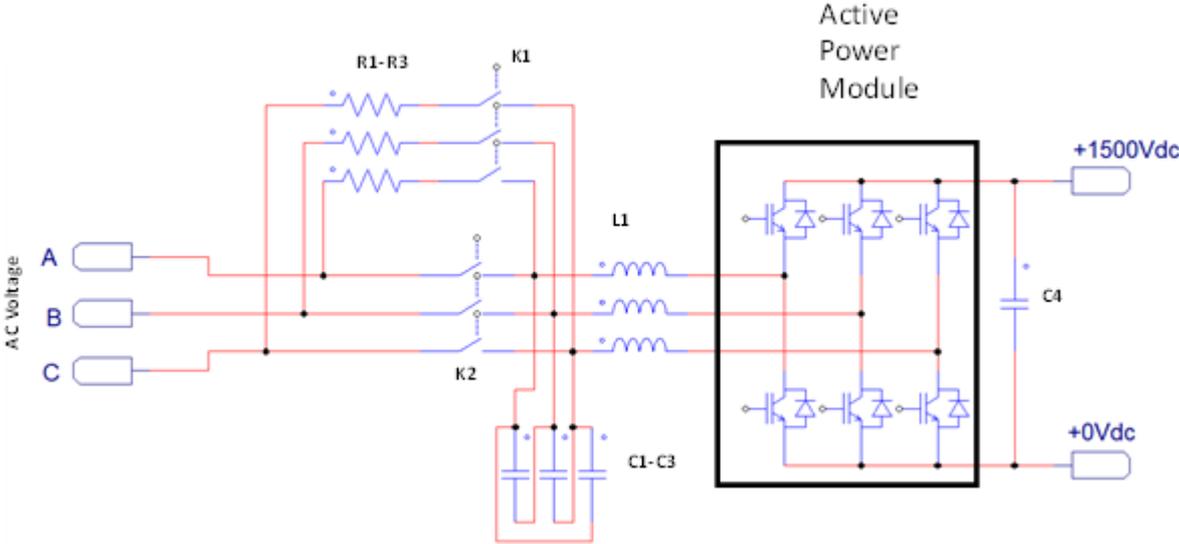
Figure 11 shows another alternative solution for pre-charge circuit using a thyristor (TH1) and a resistor (R1) plus a diode (D1). Contactor K1 has the goal of achieving galvanic isolation.

In case of the frontend power supply the pre-charging process is performed from AC line, but the goal is to the same as in previous case. See Figure 13.

The voltage at capacitor bank and current through it have similar evolution to graphics shown in Figure 12. The pre-charge time in this case is typically less than a second, because a current continues flowing though capacitor bank C1-3 after pre-charging and it generate heating in resistors R1-3.



Figure 13: Pre-charge circuit of DC power supply connected to three phases voltage line



## 7 Grid Control and Stability

The operation of systems with a large scale, high dynamics or several energy-feeding participants requires a type of grid control to ensure stability. The type of grid control depends on the number and complexity of the consumers and generators. The selection of the "Basic grid" -control (described in (ODCA, 2024)) is no longer applicable due to the test systems described in chapter **Erreur ! Source du renvoi introuvable.**

To operate at least a "Decentralized group control", droop curves must be parametrised for the participants. Properly designed, these can ensure load distribution, grid stability and reliability without higher-level load management.

The „Extended group control" can also influence Droop Control and change its parameters.

This section contains a first proposal for the control strategy to assure the stability of the D3-bus. It will be updated with the results from system simulations in June 2025 to fix a final control strategy and updated again in June 2026 with a final set of control parameters for the pilot systems.

### 7.1 Droop Curves

One advantage of the decentralized implementation of Droop Curves is that the energy sources can be prioritized. This enables peak shaving and even the operation of storage units as UPS. To do this, the devices each require a voltage measurement so that the parameters can be adapted to the grid.

The droop curves are implemented on the AFE as voltage controlled current sources, so that the devices can use lookup-tables with determined values.

With a narrow voltage band as described in chapter 0, the accuracy of the voltage measurement must be considered. This can influence the design of the droop curves and thus the subsequent stability and must be checked during the project.

The parameters consist of gradients or corner points of these and at least the opportunity for one plateau.



### 7.1.1 Interpretation

- Slopes and corner points can be set
- PV is a dynamic supplier and is not always shown in other curves  
→“Load reduction” is only necessary when no more energy can be fed back
- All participants are regarded as consumers  
→**When feeding into the DC-grid, negative current**

Figure 14: Positive counting direction of current and voltage (ODCA, 2024)

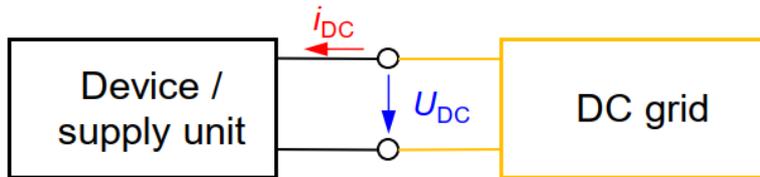


Figure 15: Example of droop curves (ODCA, 2024)

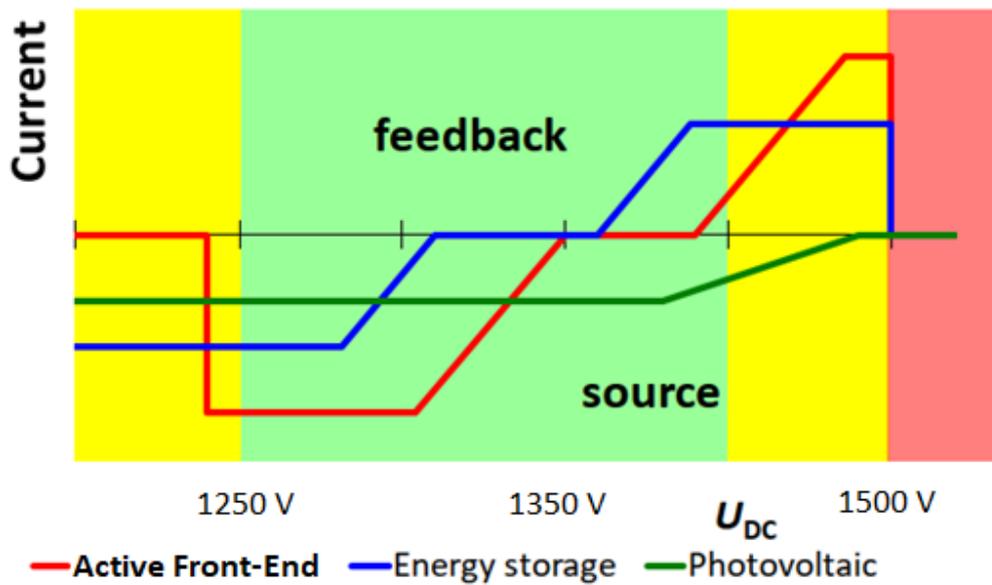
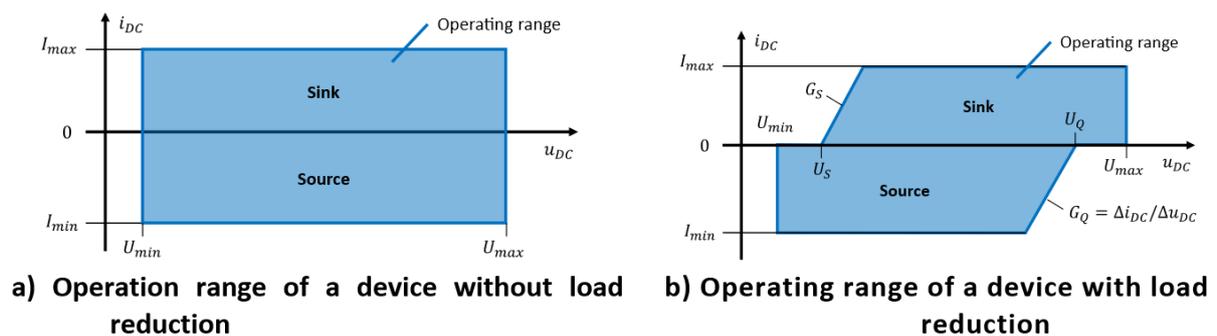


Figure 16: Operation ranges and load reduction (ODCA, 2024)



## 7.1.2 Electrolyser – 1. Example

The first test system with a focus on industrial applications has an electrolyser as its main consumer. These are not particularly dynamic and require a few seconds in which to ramp up operation. The weather-related energy fluctuation of the PV field poses a greater challenge for the dynamics of an active front end.

Figure 17: Droop curve example for AFE and PV



The droop curve of the PV (here in green) largely only describes the operating range during which energy is supplied to the grid (i.e. as a negative load according to the notation). Starting in the yellow area and also delayed after the grid has been formed by the AFE. Y-scale does not correspond to the actual values for the sake of clarity.

As far as possible, the subscriber supplies the maximum possible power and is not regulated via the voltage range.

The power of the PV is only limited by the device in the upper voltage range. Here, derating takes place due to the topology. The range (stated here as between U3 with 1425V and U4 with 1500V according to the voltage ranges) is determined by the optimum device configuration and has an influence on the curve of the AFE. In normal operation, the operation point should never reach the derating of the PV system.



In addition, the droop curve of the AFE provides the main work in this pilot plant. When operating the electrolyzers, the operating point should be on the first slope regardless of the PV (as shown in the figure as an example).

The AFE is dynamically challenged by load fluctuations and changing PV power.

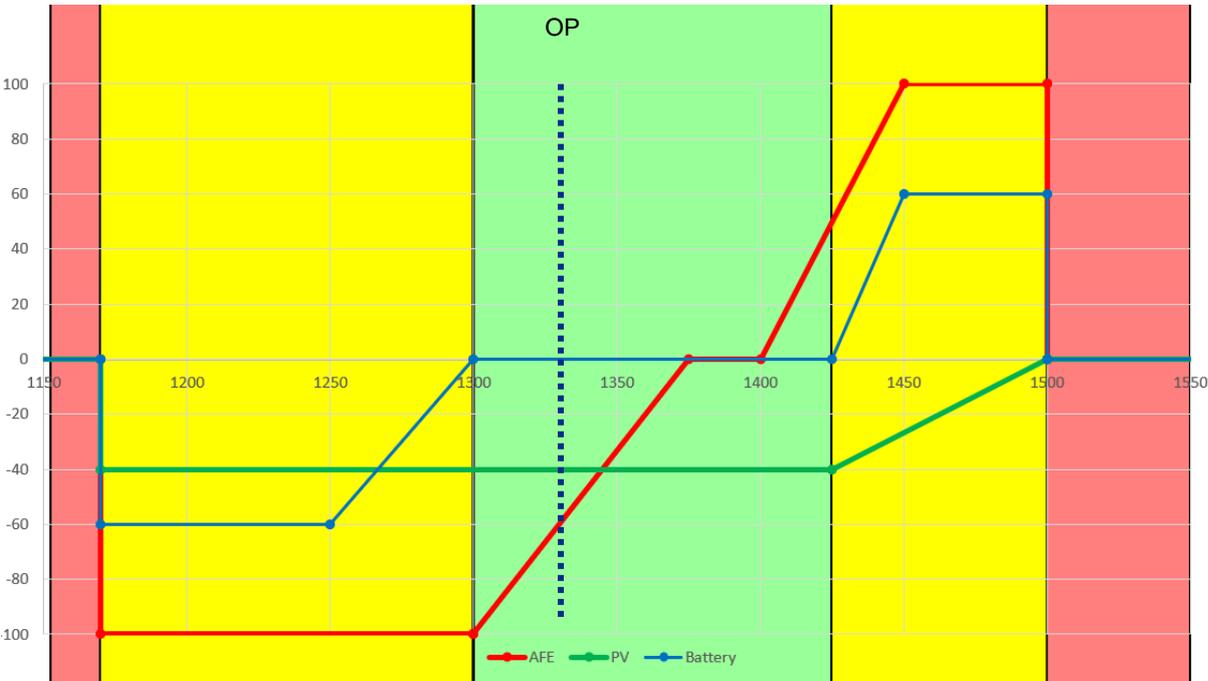
The plateau around 1375V serves as a tolerance band so that the device does not constantly switch between feed-in and feed-back in the unfavourable operating point around the intersection.

If the voltage continues to rise, such as when the electrolyzers are shut down, the AFE would feed energy back into the AC grid at the start of the second slope. It should be noted here that this should ideally be done to an appropriate extent before the PV system is derated during operation.

### 7.1.3 Data Centre – 2. Example | UPS

In the simplest and initially intended use case, the storage units for the data centre are used as a UPS (uninterrupted power supply) and the supplier only must use the droop curve to compensate for fluctuations caused by consumers and PV (e.g. due to the weather) like in the first example and is therefore not described again.

Figure 18: Droop curve example with battery as UPS



In this example, the operating point is also located on the main slope of the AFE and, depending on the state of the system, is in the overall green range (voltage band B3 according to chapter 4.3.1).

Depending on the load, the energy demand from the AC grid would be supplied via the AFE. When the nominal load (or overload) is reached or the AC supply is removed, the voltage would drop to such an extent that the OP reaches the slope of the battery, and this takes over/supports the supply. Recharging the battery would be possible if the PEMS shifts the second slope of the battery droop curve to lower voltages into the current operating area (green area). In normal operating range should the battery not be charged or discharged.

For lower energy consumption of the Data Centre during higher energy supply via PV-System, AFE feeds energy into the grid (e.g. voltage above 1400V) before the energy must be derated.

#### 7.1.4 Data Centre – 3. Example | Peak-Shaving

As an extension to the previous example, it is possible to integrate the battery more actively into operation and use it for peak shaving.

#### 7.1.5 Parameter

Overall, it is possible to achieve a major influence on the efficiency of the overall system through the design of the droop curves. To achieve optimum stability and efficiency, the influence of all participants must be considered. Some of these variables are:

- Dynamic Load (Y/N)
- PV (Dyn / Off)
- Battery for UPS / Peak-Shaving (Y/N)
- Nominal Power AFE
- Energy Management System influence
- Prioritisation of Operation States

## 7.2 Power & Energy Management System

The PEMS is responsible for extended group control and can change the droop curves of the participants manually or according to its own routines as required.



This is primarily used for the UPS functionality of the battery storage system.

It should be noted that charging and discharging cycles are balanced in the long term.

For this purpose, the equipment of both the EMS and the different devices connected to the D3-bus must establish communications (e.g. via Ethernet, Modbus TCP) with delays of hundreds of milliseconds and agree on a data model that allows the exchange of information in this regard.

In addition, once grid stability is already guaranteed, the PEMS can provide extended functionality for the energy management of the system, playing with the available degrees of freedom. In this way, algorithms such as peak shaving or load shifting can be implemented by adjusting the battery charge and discharge power setpoints, while always maintaining a sufficient energy reserve to guarantee UPS functionality.

### 7.3 Rate of voltage changes

The final system design and prior simulation must be used to determine which voltage changes are to be expected. Relatively low capacitance and high dynamics could lead to instabilities and the need to limit the voltage changes during normal operation.

### 7.4 Redundancies

Redundancies are not initially planned within the pilot plants. In further consideration, redundancies or scalable supply units could be used, for example, to increase efficiency optimisation or maintainability.

### 7.5 Nomenclature standard for droop curve parametrization

In order to transmit the droop curve behaviour to the devices connected to the D3-Bus, these curves need to be parametrized in a simple way using some setpoints and slopes.

If it is not possible to implement plateaus for droop-curves, areas with a very flat gradient are also target-oriented

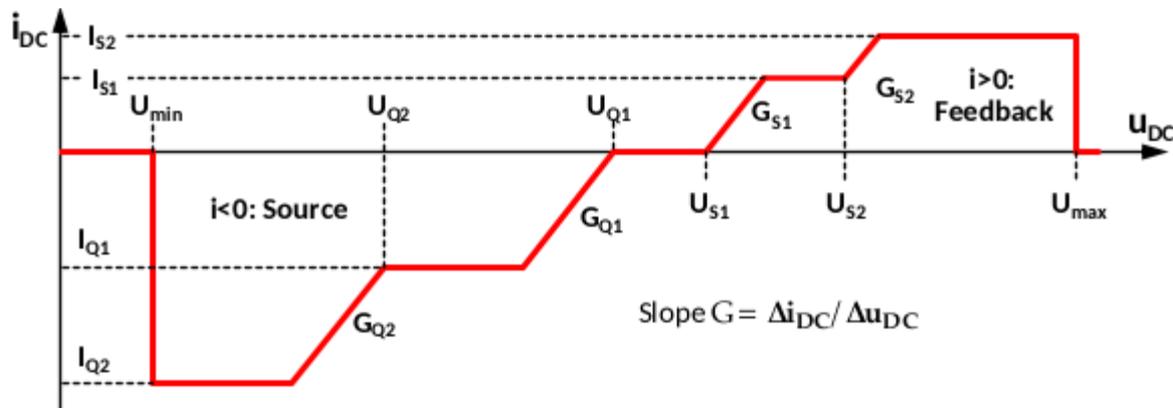


Table 6: Parameters of a droop curve (ODCA, 2024)

| Parameter  | Description  | Unit | Value range                     |
|------------|--|------|---------------------------------|
| $I_{Q2}$   | Maximum (negative) current in generation mode          | A    | $I_{Q2} \leq I_{Q1}$            |
| $I_{Q1}$   | Plateau current in generation mode                     | A    | $I_{Q1} \leq 0$                 |
| $I_{S1}$   | Plateau current in consumption mode                    | A    | $0 \leq I_{S1}$                 |
| $I_{S2}$   | Maximum current in consumption mode                    | A    | $I_{S1} \leq I_{S2}$            |
| $U_{\min}$ | Minimum voltage  | V    | $U1 \leq U_{\min} < U_{\max}$   |
| $U_{Q2}$   | Voltage at the 2 <sup>nd</sup> kink in generation mode | V    | $U_{\min} \leq U_{Q2} < U_{Q1}$ |
| $U_{Q1}$   | Voltage at the 1 <sup>st</sup> kink in generation mode | V    | $U_{Q2} < U_{Q1} \leq U_{S1}$   |
| $U_{S1}$   | Voltage at the 1 <sup>st</sup> kink in feed-back mode  | V    | $U_{Q1} \leq U_{S1} < U_{S2}$   |
| $U_{S2}$   | Voltage at the 2 <sup>nd</sup> kink in feed-back mode  | V    | $U_{S1} < U_{S2} \leq U_{\max}$ |
| $U_{\max}$ | Maximum voltage  | V    | $U_{\min} < U_{\max} \leq U4$   |
| $G_{Q2}$   | Slope of droop curve section 2 in generation mode      | A/V  | $G_{Q2} > 0$                    |
| $G_{Q1}$   | Slope of droop curve section 1 in generation mode      | A/V  | $G_{Q1} > 0$                    |
| $G_{S1}$   | Slope of droop curve section 1 in feed-back mode       | A/V  | $G_{S1} > 0$                    |
| $G_{S2}$   | Slope of droop curve section 2 in feed-back mode       | A/V  | $G_{S2} > 0$                    |



Figure 19: Sections of a droop curve (ODCA, 2024)



## 8 Protection

The protection scheme elaborated in this chapter is further elaborated in Task 5.2 and detailed in deliverable D5.4. Once available, the deliverable D5.4 entirely replaces this chapter.

### 8.1 DC Protection of the D3-bus system

#### 8.1.1 Overvoltage and undervoltage protections:

All converters must have overvoltage and undervoltage protections, which allow to operate temporary or to stop operation instantaneously according to the voltage table defined in task 3.2. Any overvoltage or undervoltage should not damage the power converter.

A **voltage transducer** is necessary at the DC lines connection points of all converters for implementation of those protections. However, this transducer itself is not enough. The implementation of **L-C filter** at DC line connection points is needed to protect converter against short term overvoltages lasting less than 1ms (it will be mainly a capacitor filter to reduce serial inductance).

**Surge arresters** also connected between the DC lines and ground (midpoint of  $\pm 1500\text{VDC}$  lines) protect against very short and high overvoltage ( $<200\mu\text{s}$ ). They are included in the frontend power supply at both positive and negative outputs.

Converters, which operate as current or voltage power supplies such as the front-end power supply, demand ultra-fast circuit breakers to disconnect the power supply in case of short circuit or very low overvoltage. In this case the reaction time is less than 50 $\mu\text{s}$ .



### 8.1.2 DC overcurrent protections:

This is a mandatory protection. It is necessary to add a **current transducer** at the connection point or to estimate this input current any way. If the current is over a first threshold level, the overload routine is activated. It is a typical solution to implement  $I^2t$  calculation. When  $I^2t$  calculated value reaches the defined threshold level, the converter stops operation and try to restart automatically and manually. If the failure continues after few attempts, the converter goes to lockout stage, and the root cause of the fault must be found.

### 8.1.3 Short-circuit protection:

Converter must be protected against external short circuit. The permanent voltage and DC current surveillance are a good method to detect line short circuit. When a **blocking diode** is possible to connect at the input of converter, it solves the problem. However this diode reduces the converter efficiency and in case of converters, which operate as voltage or current source, this diode solution is not possible. Source power supply such as the frontend power supply, PV converters and reversible battery chargers are in this case. For solving this problem, there should be **internal protection**, which allow disconnect the circuit in case of the DC line short circuit such as fuses, ultrafast circuit breakers. These solutions also protect converters against internal short circuits, but this case is not analysed here.

### 8.1.4 Galvanic Isolation:

When an external short circuit occurs, disconnection of all converters to determine what of them generated this short circuit is a necessary manoeuvre.

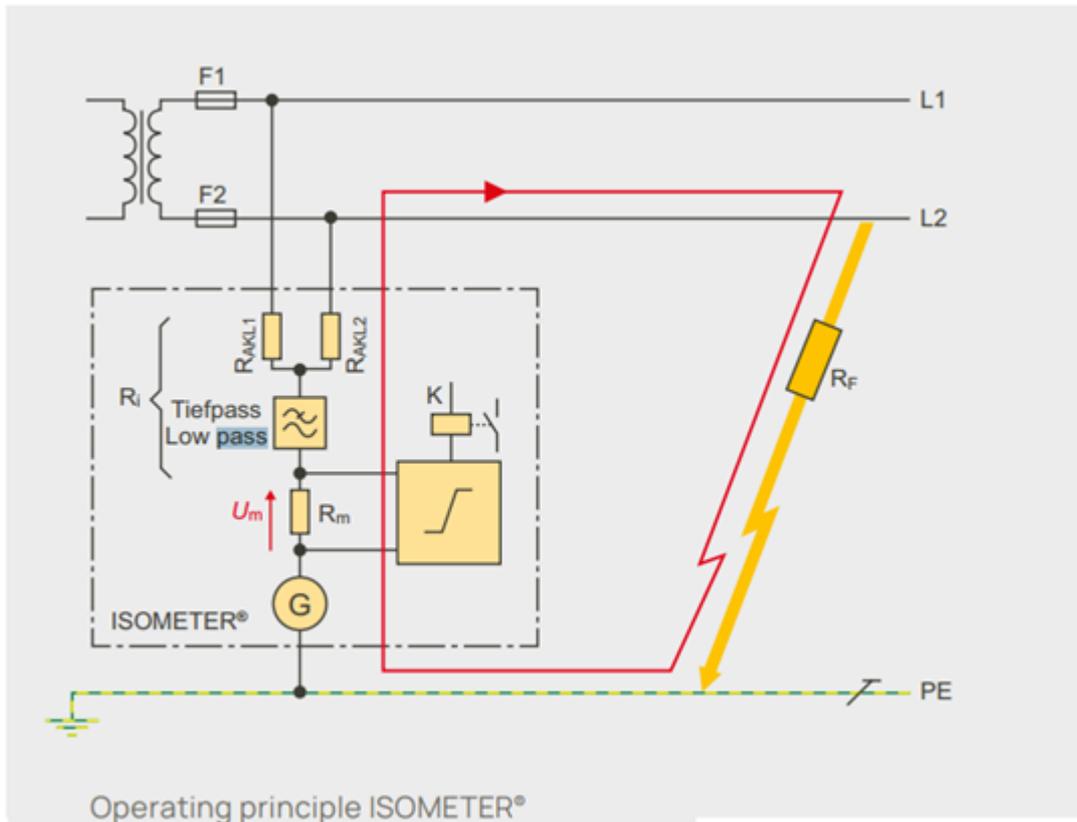
The converter should start to connect one by one to determine faulty converter in case faulty converter is unknown. The galvanic isolation and internal overcurrent protection can be achieved with an ultrafast DC circuit breaker or with contactor plus fuses. The solution of circuit breakers is desirable for cases when there is common line for several converters and loads to avoid frequent fuse substitutions.

### 8.1.5 DC line isolation:

DC line isolation should be monitored continuously. There are some devices available in the market, which allow to measure DC and AC isolation for IT systems. An example of **isolation monitoring** device is shown in Figure 20. This trademark of this device is called "Isometer" manufactured by Bender GmbH.



Figure 20: Isolation monitoring device



There are several other similar products available in the markets manufactured by other companies.

Those monitoring devices are for DC and AC lines up to several kV with line capacity of 4mF. The application of this kind of isolation monitoring devices could be suitable for  $\pm 1500\text{Vdc}$  lines, however it must be studied due to large capacity connected to these DC buses.

#### 8.1.6 Ground fault protection:

The connection point to ground should be provided with a **current sensor** or **current relay** which can allow tripping an alarm in case of ground fault current reaching defined threshold levels. This information is sent to all converters by means of communication bus and a defined manoeuvres start.

Voltage presence: The converters need **annunciation signal** to show that voltage is over 50V and avoid accessing inside the converter and people electrocution. This annunciation signal and corresponding safety instruction about maximum voltage for accessing should be visible.



## 8.2 DC Protection on the output of the appliance driver or powerbox

The necessity of protection devices between the appliance drivers and the applications will be discussed and decided in WP6 and T5.2 (D5.4).

Some first suggestions:

- A DC current undervoltage protection and earth leakage protection shall also be considered in the DC/DC converter.
- Circuit breakers should be installed between the power box and the IT racks.

## 8.3 AC Protection

### AC line protections:

All this protection impacts only on the front-end power supply, which is a single power supply connected directly to AC line.

- **Overvoltage and undervoltage protections:** There are voltage transducers connected at the secondary of the medium voltage transformer, which allow to measure the AC voltages. If voltage variation exceeds a  $\pm 10\%$  the nominal, the converter stops operation or follows agreed procedure. The operation is restarted when AC voltage is within defined voltage range again.

There are surge arresters connected from each AC phases to ground to protect converter against short term high overvoltages.

- **Overcurrent protections:** The phase current is measured by AC current transducers. when AC current is overs threshold level of overcurrent protection, but lower than the threshold level of short-circuit protection, the overcurrent routine starts. If the overcurrent routine reaches its internal limit, the converter is stops.

The converter can restart automatically or manually. If the overcurrent continues after several attempts the converter goes to lockout stage.

- **Short-circuit protection:** Short circuit protection trips when the input current surpasses the threshold short-circuit current level, in this case the AC circuit breakers open. The short circuit protection and overcurrent one can be implemented internally in the AC circuit breakers if the circuit breaker have this performance.
- **AC galvanic isolation:** The isolation is achieved by means of both AC circuit breakers connected at primary and secondary of medium voltage transformer. Theses circuit breakers disconnect the rest of the converter circuit the from the energized parts and allow accessing safely inside the converter.



- **Ground leakage protection:** When leakage current to ground appears at the AC circuit these current returns by the same transducer as in case of the DC line. There is a possibility to distinguish if the leakage current is AC or DC by means of signal filtering.
- **Wrong phase sequence:** The control circuit of the frontend power supply detects wrong phase rotation due to wrong phase connection during installation. When this alarm trips, the converter does not start operating.

The AC circuit breaker in the AC-to-DC rectifier shall include LSIG protection.

## 9 Annexes

### 9.1 Sources

ODCA. (2024). *DC-INDUSTRIE2 System Concept*.



## 10 Partners

