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Tractors and machinery for agriculture and forestry — Electrical high-power interface 700 V DC / 480 V AC —

Part 5:
DC operation mode

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Contents

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This document was prepared by Technical Committee ISO/TC 23, *Tractors and machinery for agriculture and forestry*, Subcommittee SC 19, *Agricultural electronics*

A list of all parts in the ISO 23316 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

ISO 23316-1 describes the general purpose and structure of standards in the ISO 23316 series, including common elements and definitions shared within all parts of the ISO 23316 series.

The purpose of the ISO 23316 series is to provide design and application standards covering implementation of electrical high power interface with a nominal voltage of 700 VDC/480 VAC for agricultural and forestry machinery.

The ISO 23316 series specifies physical and logical interface requirements that provide interoperability and cross compatibility for systems and equipment operating at nominal voltages of 700 VDC/480 VAC.

The following are not within the scope of ISO 23316:

— service, maintenance, and related diagnostics;

— functional safety;

— control strategies for high power sources and loads;

— application-specific strategies and operational modes;

— component design;

— energy storage systems, e. g. super-capacitors or batteries;

— multiple electrical power sources supplying a common DC link.

It is permitted for partial systems or components to be compliant to the ISO 23316 series by applying all applicable requirements, e.g. for the plug, receptacle or inverters, on a tractor or implement.

NOTE   If a DC-mode only HPI is provided, it is not necessary to comply with part 4 describing AC-mode, as it is not applicable. If an AC-mode only HPI is provided, it is not necessary to comply with this document, as it is not applicable.

Tractors and machinery for agriculture and forestry — Electrical high-power interface 700 V DC / 480 V AC —

Part 5:
DC operation mode

1 Scope

This document specifies measures applicable to the class B2 voltage DC bus of a supply system which is intended to power detachable electrical CS(s).

— electrical specification of the high power interface

— operating modes (e. g. initialization, normal operation, energy feedback, connect/disconnect procedures and disconnect in case of malfunction)

— Communication parameters (basic framework: signals, ranges, units, states of supply system and CS)

The document contains simplified electrical diagrams showing specific aspects of the required functionality.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 16230-1:2015, *Agricultural machinery and tractors — Safety of higher voltage electrical and electronic components and systems — Part 1: General requirements*

ISO 23316-1, *Tractors and machinery for agriculture and forestry — Electrical high-power interface 700 V DC / 480 V AC — Part 1: General*

ISO 23316-2, *Tractors and machinery for agriculture and forestry — Electrical high-power interface 700 V DC / 480 V AC — Part 2: Physical interface*

ISO 23316-3, *Tractors and machinery for agriculture and forestry — Electrical high-power interface 700 V DC / 480 V AC — Part 3: Safety requirements*

ISO/FDIS 23316-6:—[1], *Tractors and machinery for agriculture and forestry — Electrical high power interface 700 V DC / 480 V AC — Part 6: Controls communication*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 23316-1, ISO/FDIS 23316-6:— and the following apply.

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1) Under preparation. Stage at the date of publication: ISO/FDIS 23316-6:2023.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1.1
device under test
DUT
single component or combination of components as defined to be tested

[SOURCE: ISO 10605:2008, 3.3]

3.2 Symbols

$C_{DC\ src}$	DC link capacitance PS
$C_{DC\ ld}$	DC link capacitance CS
$C_{y\ ld}$	Y-Capacitor CS
$C_{y\ src}$	Y-Capacitor PS
L_{cab}	cable inductance
$L_{i\ src}$	inner source inductance
$R_{i\ src}$	inner source resistance
R_{cab}	cable resistance
R_{cont}	contact resistance
m	inverter modulation index representing the amplitude of the fundamental output voltage U_0 normalized by the DC supply voltage U_{DC}, so $m= U_0/U_{DC}$
$\triangle U$	voltage ripple
C_{DC}	DC link capacitor
I_{pk}	peak current
I_{rms}	root mean square current
f_{sw}	switching frequency
min	minimum

4 System overview

4.1 General

Key

ACL	AC load (e.g. electric motor)
APP	application
C	controller of a device
C_{DC}	DC link capacitor
CE	combustion engine
DCLNK	DC link
G	generator (as example of an electric power source)
HPI-C	High Power Interface - Control
HPI-MC	High Power Interface – Master Control
INV	inverter (DC/AC converter)
REC	rectifier (AC/DC power converter)
S	switch (contactor or solid state switch, including pre- and discharge unit)
S-C	switch controller
T	transmission
TC	task controller
TIM-C	Tractor Implement Management Client
TIM-S	Tractor Implement Management Server
VT	virtual terminal (user interface, e.g. display)
I	supply system
II	consumer system
1	high power interface
2	ISOBUS connector
3	power lines
4	ISOBUS
5	supply system communication bus (e.g. tractor bus)
6	consumer system communication bus (e.g. implement bus)

7	interlock signal
8	feedback signal (by e.g. a sensor)
9	interlock signal line breaker
———	power connection
- - - -	signal/bus connection
....	optional connection
══════	defines focus of document

Figure 1 — Exemplary system schematics

The system consists at least of an electrical PS with generator and control providing DC power on a DC link and a CS, which is connected by an HPI and communication line in accordance with ISO/FDIS 23316-6:—. System schematics are shown in Figure 1.

NOTE   Depending on design, a discharge unit can be needed for implements.

The architecture of the load depends upon the specific application and can have any combination of resistive, inductive and capacitive elements. The common base is the voltage provided by the source (and specified in the subsequent chapters) and the communication interface according to ISO/FDIS 23316-6:—. A voltage source can have multiple HPIs.

The minimum VC-B2 system consists of at least one PS and one APP. The VC-B2 system is based on an IT system. Each implement may contain many different VC-B2 devices.

4.2   Operation with single CS

At the simplest level, only one CS (e.g. implement) is attached on the supply system (e.g. tractor), where the PS is located. The single CS can contain one or more independent VC-B2 devices. Such a configuration is shown in Figure 2 and is the basis for the following figures with MCS.
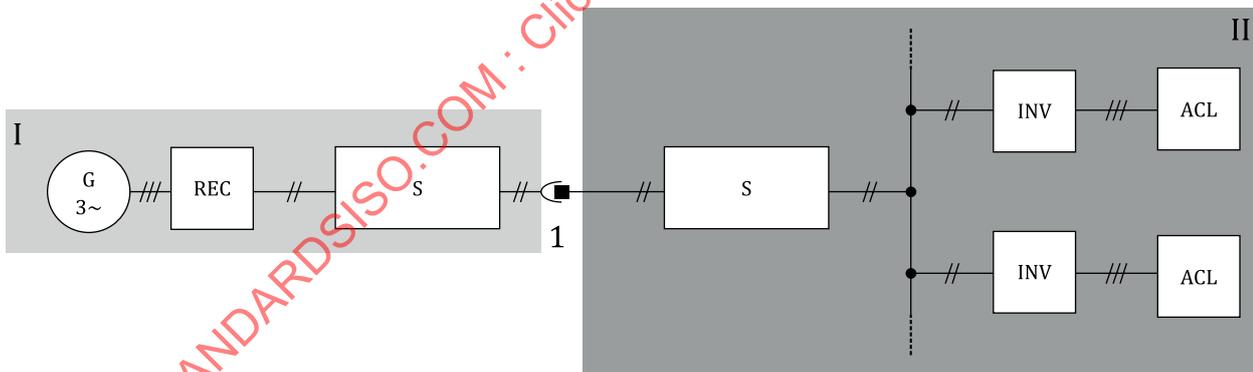
Key

ACL	AC Load (e.g. electric motor)
G	Generator
INV	Inverter
REC	Rectifier
S	Pre- / discharge / disconnecting device
I	supply system (e.g. tractor)
II	consumer system (e.g. implement)
1	high power interface

Figure 2 — Single implement block diagram

4.3 Operation with MCS

It is also possible to attach an MCS to a supply system (e.g. tractor). Each can contain one, or more VC-B2 devices. If an MCS is attached to one supply system, each CS needs its own HPI-C. Figures 4 to 6 show some, but not all possible, configurations.

The first supply system in the topology (typically located on tractor, or a PTO generator) shall provide the sum of the power of the connected CS. In case of power/current restrictions due to higher total demand compared to capabilities, one of these two load balancing options shall be used.

a)   The HPI-MC shall control the power distribution of all other connected combinations.

b)   The HPI-MC shall control the power distribution of the first supply system connected subsystems (which consist of several VC-B2 devices).

Figure 3 shows a configuration where several CS are attached on supply system, and each has its own HPI (maximum allowed number of implements in accordance with ISO 11783).
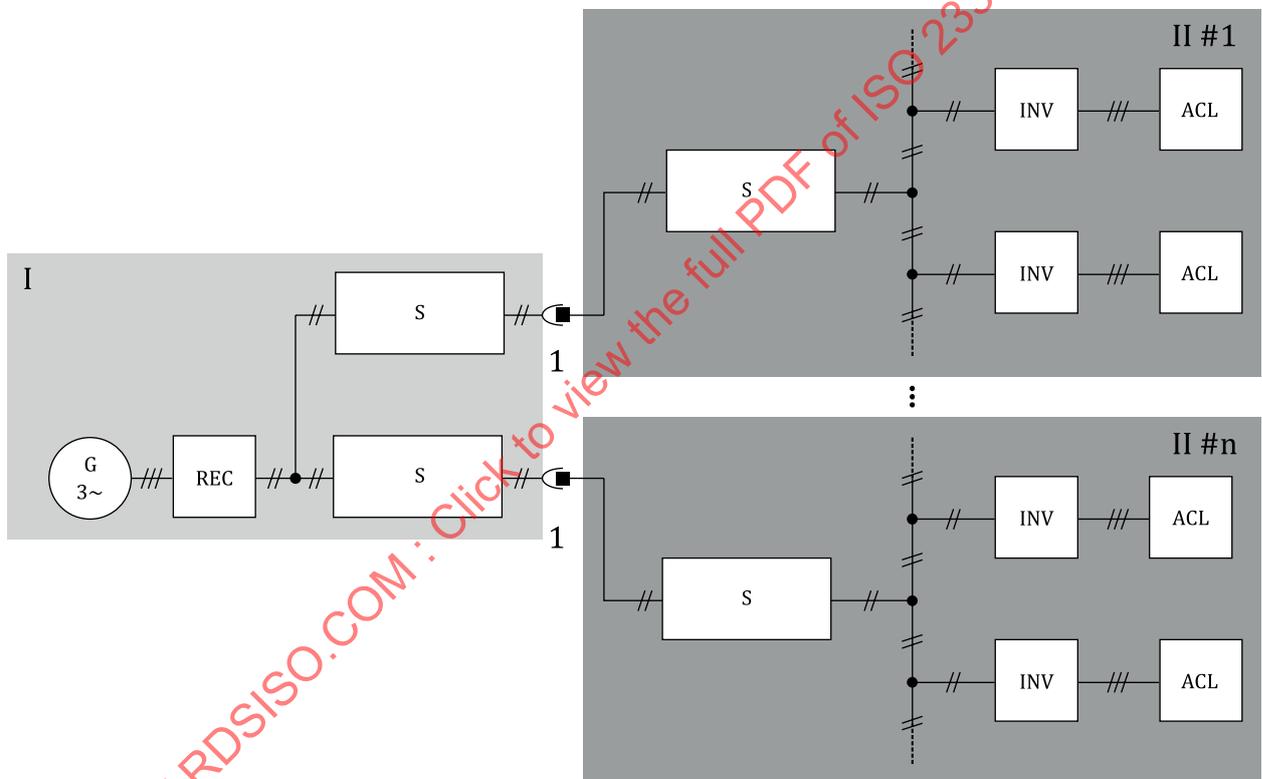
Key

ACL   AC load (e.g. electric motor)

G   generator

INV   inverter

REC   rectifier

S   pre-/discharge/disconnecting device

I   supply system (e.g. tractor)

II   consumer system (e.g. implement)

1   high power interface

Figure 3 — Configuration with several parallel CS each at a separate connector

Figure 4 shows a configuration where a CS is attached on supply system's front and several CS are attached on supply system's rear and each has its own HPI.
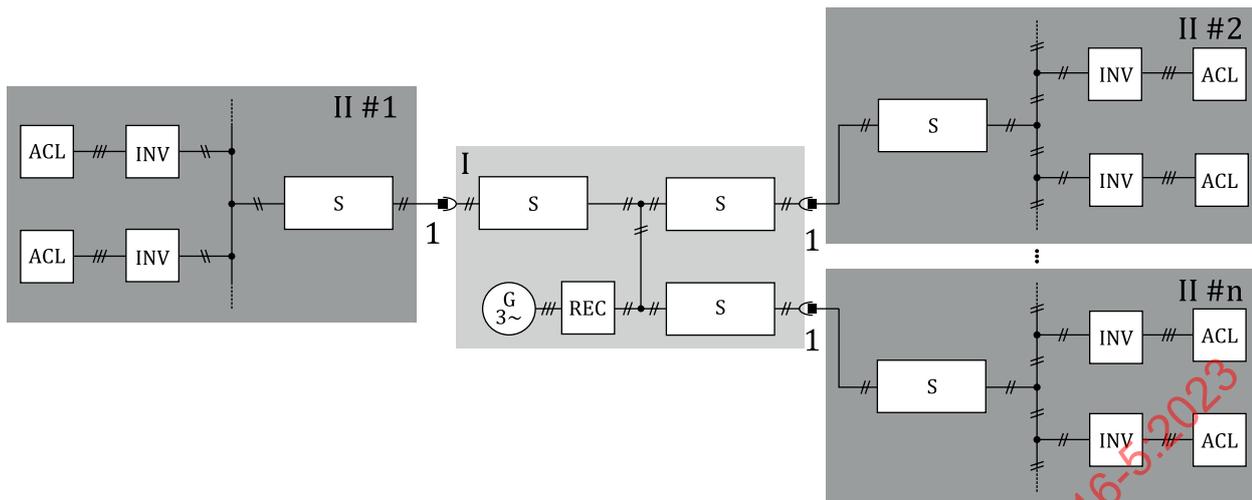
Key

ACL   AC Load (e.g. electric motor)
G   generator
INV   inverter
REC   rectifier
S   pre-/discharge/disconnecting device
I   supply system (e.g. tractor)
II   consumer system (e.g. implement)
1   high power interface

Figure 4 — Configuration with a front CS and several rear CSs each with a separate connector

Figure 5 shows a configuration where three CS are attached in series, thus only one tractor HPI is used and two CS are providing the HPI to the following one.
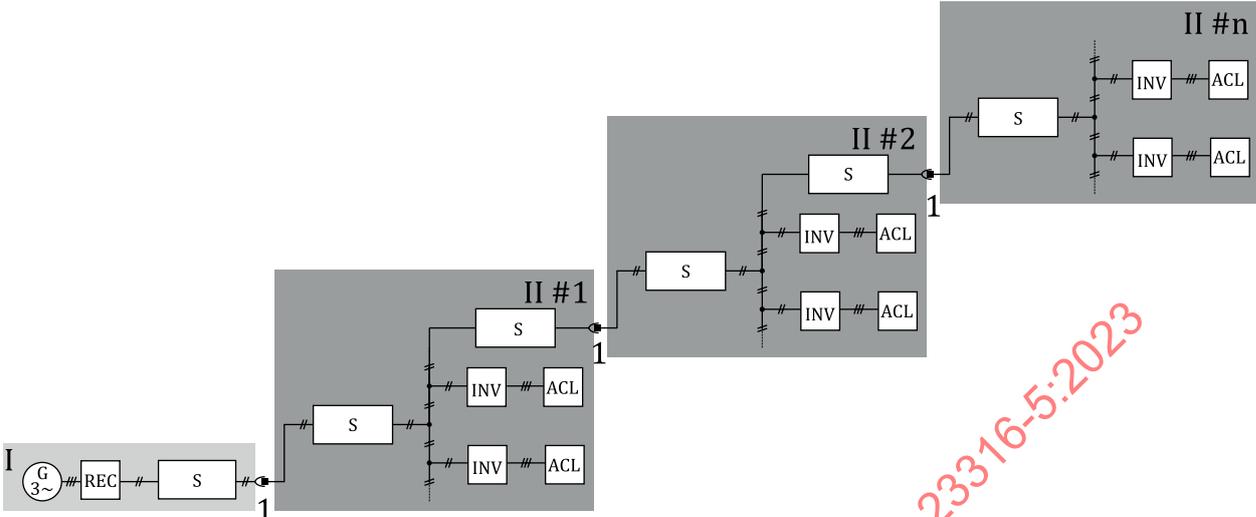
Key

ACL   AC load (e.g. electric motor)

G   generator

INV   inverter

REC   rectifier

S   pre-/discharge/disconnecting device

I   supply system (e.g. tractor)

II   consumer system (e.g. implement)

1   high power interface

Figure 5 — Configuration with three CS in series

Figure 6 shows a configuration where series and parallel connection of CSs are combined.
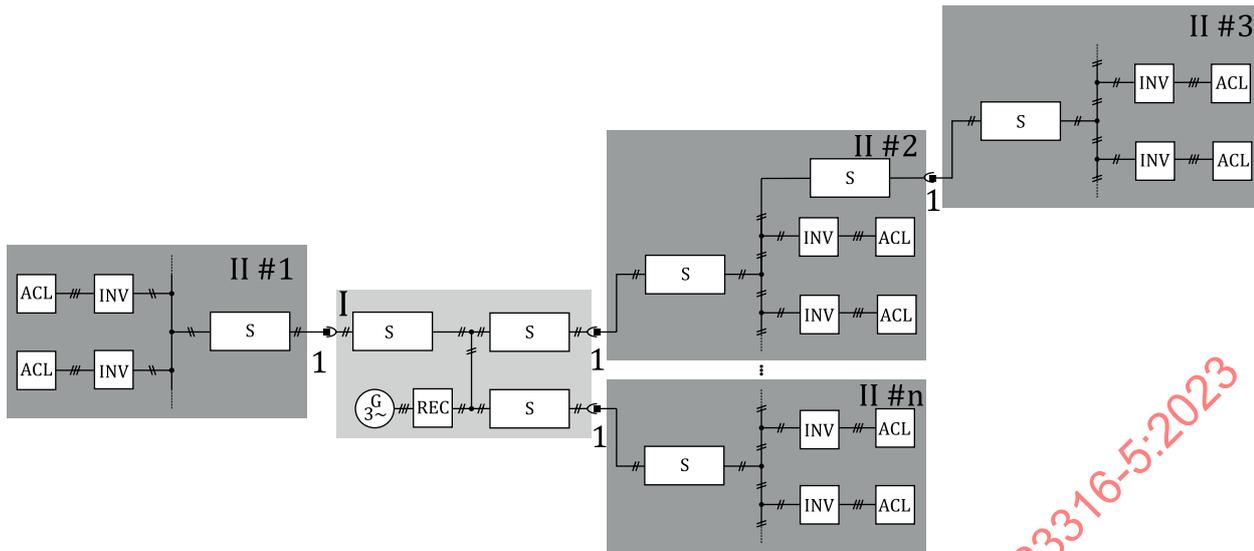
Key

ACL   AC load (e.g. electric motor)
G   generator
INV   inverter
REC   rectifier
S   pre-/discharge/disconnecting device
I   supply system (e.g. tractor)
II   consumer system (e.g. implement)
1   high power interface

Figure 6 — Configuration with front CS, a single rear CS and two rear CS in series

5   DC specification

5.1   Voltage form and quality

5.1.1   System voltage: values and ranges

For the purposes of this document, the voltage values and ranges given in ISO 23316-1 apply.

5.1.2   Voltage ripple

5.1.2.1   General

Periodic voltage ripple is generated due to residual incomplete suppression of an alternating wave after rectification from switching of the inverters used in the PS and loads.

5.1.2.2   Ripple specification for a power source (PS)

For the first PS, ±2 % of the nominal voltage shall not be exceeded.

NOTE   If an implement serves as PS, it might not be possible to satisfy this requirement as well.

5.1.2.3 Ripple specification for load(s)

±5 % of the nominal voltage shall not be exceeded.

NOTE   Different levels for the PS and loads are defined to avoid exceeding the specified limits in case of DC bus resonances.

5.1.3 Continuous DC current

The continuous DC current is the current, which the PS is able to supply.

The maximum continuous DC current is restricted by three limits:

— continuous current the PS is able to supply, which is $I_{cont\ source} = P_{cont\ source}/U_{nom}$ (Signal according to ISO/FDIS 23316-6:—: "PC/S current capability–continuous)";

— current carrying capability of the HPI (as defined in ISO 23316-2:2023, 4.5.6);

— continuous current limitation by the cable cross section from HPI to CS, defined and transferred by the HPI-C (e.g. implement) to the HPI-MC (e.g. tractor) (Signal according to ISO/FDIS 23316-6:—: "Load current demand– maximum continuous").

The lowest value of these limits is the maximum current, which can be supplied by the PS continuously. This is transferred from the HPI-MC to the HPI-C (Signal according to ISO/FDIS 23316-6:—: "PC/S current calculated–continuous").

5.1.4 Peak current

Each system part (PS and load) has its own peak current limit. The peak current is the maximum amount of current which the output is capable of sourcing for brief periods of time. Characterizing values are amplitude, duration and minimum repetition rate. It mainly depends on the physical limits of the electrical hardware used (current carrying capability, heat dissipation, etc.).

Applications on implements or attachments can have load variations causing the occurrence of peak currents. The aim is not to overload the PS, cables and HPI contacts by the load.

The maximum peak DC current is restricted by three limits:

— peak current the PS is able to supply, which is $I_{peak\ source} = P_{peak\ source}/U_{nom}$ (Signal according to ISO/FDIS 23316-6:—: "PC/S current capability–peak");

— current carrying capability of the HPI (as defined in ISO 23316-2:2023, 4.5.6);

— peak current limitation by cable cross section from HPI to CS, defined and transferred by the HPI-C (e.g. implement) to the HPI-MC (e.g. tractor) (Signal according to ISO/FDIS 23316-6:—: "Load current demand–maximum peak").

The lowest value of these limits is the peak current, which can be supplied by the PS. This is transferred from the HPI-MC to the HPI-C (Signal according to ISO 23316-6: "PC/S current calculated–peak").

The following cases of operation will occur:

a) $I_{peak\ (PS)} > I_{peak\ (load)}$ → operation possible

b) $I_{peak\ (PS)} \le I_{peak\ (load)}$ → application specific, if operation possible

c) $I_{peak\ (PS)} << I_{peak\ (load)}$ → use of application is unlikely

5.1.5 Current specific communication parameters

To establish communication between supply system and CS, the PS shall send its specific continuous and peak current limits as defined in ISO/FDIS 23316-6:—.

NOTE 1   The CS decides with respect to the specific application, if normal or restricted operation is possible.

NOTE 2   In case of multiple HPIs, the operator shall decide if the operation makes sense.

5.1.6 Voltage dips and recovery time

Voltage dips are the temporary deviation of the DC bus voltage from its normal value. It does not include the periodic ripple.

If the current requested by a CS exceeds the maximum current supply capability of the PS for a limited time period, the voltage will dip. Alternatively, if the CS is characterized by a rapidly changing rate of the requested power (dimension: kW/s) the source voltage may dip. Recovery time is determined by peak current capability/request of PS and load and their control loop responses.

Communication between supply system and CS during initialization shall be in accordance with ISO/FDIS 23316-6:—. First, the PS shall provide its system limits. With this information the CS shall decide whether normal, restricted or no operation is possible (application specific).

5.1.7 Overvoltage protection

5.1.7.1 Operational states leading to overvoltage in the DC system

Overvoltage can be caused by the following events:

— Energy feedback from load to PS. For more details refer to 5.3.7 "energy feedback").

— Energy surplus in the DC link circuit (energy coming from both sides)

— Oscillations between components on the DC link circuit

5.1.7.2 Functional requirements

Measures to avoid overvoltage shall be taken on the PS and may additionally be taken on the CS to limit the voltage to a level as defined in ISO 23316-1. Details are defined in 5.3.7.

Depending on the amount of the expected overvoltage, one or more of the following measures shall be taken:

— dissipating energy by brake chopper;

— storing surplus energy in appropriate devices (e.g. capacitor, battery, flywheel storage);

— cutting off the system from supplies;

— feeding back energy to energy source, e.g. diesel engine.

5.1.8 Overcurrent protection

5.1.8.1 Operational states leading to overcurrent in the DC system

Overcurrent can be caused by the following events:

— power requirement of the load exceeds the maximum available power (of the PS);

— high energy feedback from load to PS;

— system malfunctions (e. g. short-circuits on PS or load).

5.1.8.2 Continuous and peak current on PS and CS

The maximum current, which is expected, refers to the installed power each on PS (tractor) and CS (implement). Thus, PS and CS(s) have their own current carrying capability, which shall not be exceeded in order to protect their own devices (e.g. cables, connectors, switches, etc.). In the connected DC-system, a continuous current and a peak current for the system are defined. They are determined by the PS and depend on the maximum power the PS is able to provide. The continuous current which can be transferred by the HPI as a maximum is a limit which shall not be exceeded (see ISO 23316-2). These figures are absolute system limits.

5.1.8.3 Requirements

5.1.8.3.1 General

Each unit (PS or load) connected to the DC link circuit shall prevent the current exceeding the maximum permitted value for itself.

Devices to prevent from overcurrent shall be one of the following:

— fuses;

— circuit breakers;

— switches (e.g. relays).

NOTE   The situation can be compared with a standard grid application: Incoming lines to a house are fused with higher current values than separate rooms or special equipment within a house.

5.1.8.3.2 PS current less than load current

This applies if the current provided by the PS is less than the maximum which can be consumed by the load $I_{max (PS)}$ <= $I_{max (load)}$.

This is a special situation. If the tractor-implement combination is allowed to work (to be handled during initial communication, application specific, see ISO/FDIS 23316-6:—), the maximum power on load side shall be limited to a value so that the maximum current of PS is not exceeded. Otherwise the operation of this specific tractor-implement combination shall not be allowed. Each part of the system shall protect itself against overcurrent.

In case of multiple implement operation the sum current of all implements can exceed the current capability of the PS (see also "multiple implements operation"). During initialization the sum current shall be matched.

5.1.8.3.3 Source current greater than load current

$$I_{peak(PS)} > I_{peak(CS)}$$

In this case, the load-source combination is operating within the specified limits. Therefore, no overload is occurring.

5.1.8.4 Overcurrent protection requirements

PS and load shall be protected against overcurrent. Because the PS can supply the load up to its specified maximum, an overcurrent protection device (OPD, e.g. fuses, circuit breakers, switches) is not sufficient. Typically, the PS inverter has an electronic current limitation. On the CS side, OPDs shall protect devices and sections of different cable cross sections. See Table 1 and Figure 7.

Table 1 — Overcurrent protection requirements

PS	CS
cross section shall be dimensioned according to maximum current to be transferred	cross section close to HPI shall be dimensioned to transfer the overall CS current
PS converter shall have an electronic overcurrent protection, so no OPD required	"general" OPD shall protect the cable from HPI to distribution box
	single OPD (fast-blow) shall protect each individual drive unit (cable cross section and OPD usage according to individual current consumption), can be part of the inverter

Key
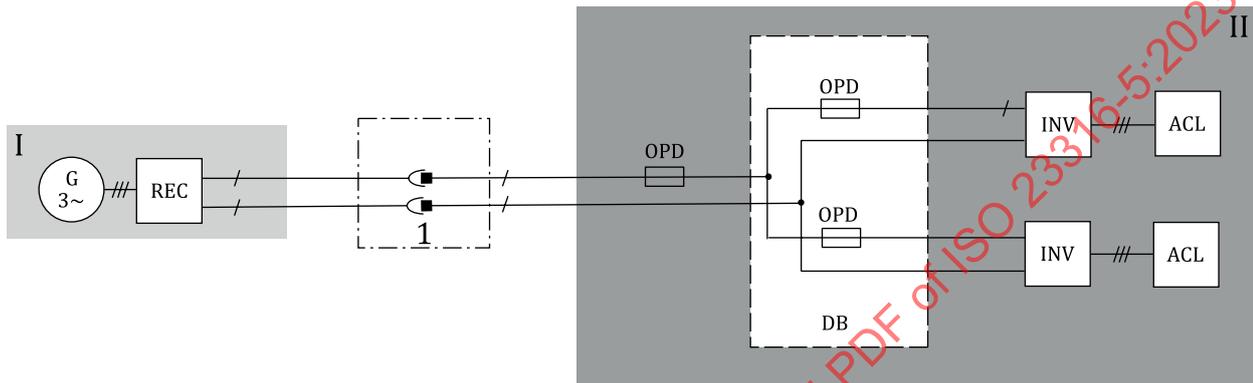
ACL   AC load (e.g. electric motor)
DB   distribution box
G   generator
INV   inverter
OPD   overcurrent protection device
REC   rectifier
I   supply system (e.g. tractor)
II   consumer system (e.g. implement)
1   high power interface

Figure 7 — Simplified dc bus diagram for a supply system and CS showing OPD locations

5.1.9 System inductance

The system inductance is a parasitic value, which mainly is a result of the VC-B2 DC harness length and geometry in the system (consisting of PS, load and HPI).

NOTE   An expected value range is helpful with regard to the equivalent circuit diagrams, see B.4).

5.1.10 DC link capacitance

5.1.10.1 General

The capacitance of the DC link capacitors connected between the + and – lines of the DC link circuit in the PS or load(s).

The DC voltage typically is provided by an inverter. The switching frequency and its harmonics are present on the DC side of the inverter and smoothened by a DC link capacitor in order to fulfil the permitted voltage ripple. Commonly, each inverter connected to a DC link system contributes to the overall system DC link capacitance.

5.1.10.2 Requirements

PS and CS shall conform with the allowed voltage ripple. This results in a DC link capacitance value on PS and load(s) (see 5.1.3 "voltage ripple").

The maximum amount of DC link capacitance defined in 5.2.1 "value ranges" shall not be exceeded.

NOTE 1   In order to ensure a correct pre-charging procedure, the actual capacitance values used on the CS are communicated to supply system according to ISO/FDIS 23316-6:—. A capacitance value of zero means that the CS will do the pre-charge on its own.

NOTE 2   Approaches for a first rough estimate of the total DC link capacitance are listed in Annex A.

5.1.11 Y-capacitors, parasitic capacitances

Y-capacitors are part of an inverter and connect positive and negative wires to the chassis in order to fulfil EMC regulations. Parasitic capacitances result from system geometry (e.g. stray capacitance between positive and negative wires to chassis).

The capacitances shall taken into account to ensure the integrity of the IT system. If the energy stored in all Y-capacitors (required to fulfil EMC regulations) and parasitic capacitances of the system exceed a certain value, dangerous currents through human body can occur under certain fault conditions.

To avoid dangerous currents through human body, follow the protection measures in accordance with ISO 23316-3 and ISO 16230-1.

5.1.12 DC Link pre-charging

5.1.12.1 General

A controlled charging of a DC link capacitor equalizes its voltage with a source to limit the surge current in case of a low impedance connection.

To achieve this, the following methods may be used to perform the pre-charge process:

— Passive pre-charge: Pre-charge process performed using a resistor, in order to reduce the peak current.

— Active pre-charge: Pre-charge process performed using power electronics to control the pre-charge current over time.

5.1.12.2 Type and position of pre-charge unit

The supply system (typically tractor) shall provide at least a passive pre-charge unit to charge the DC link capacitors. Alternatively, an active pre-charge unit via using power electronics may be installed.
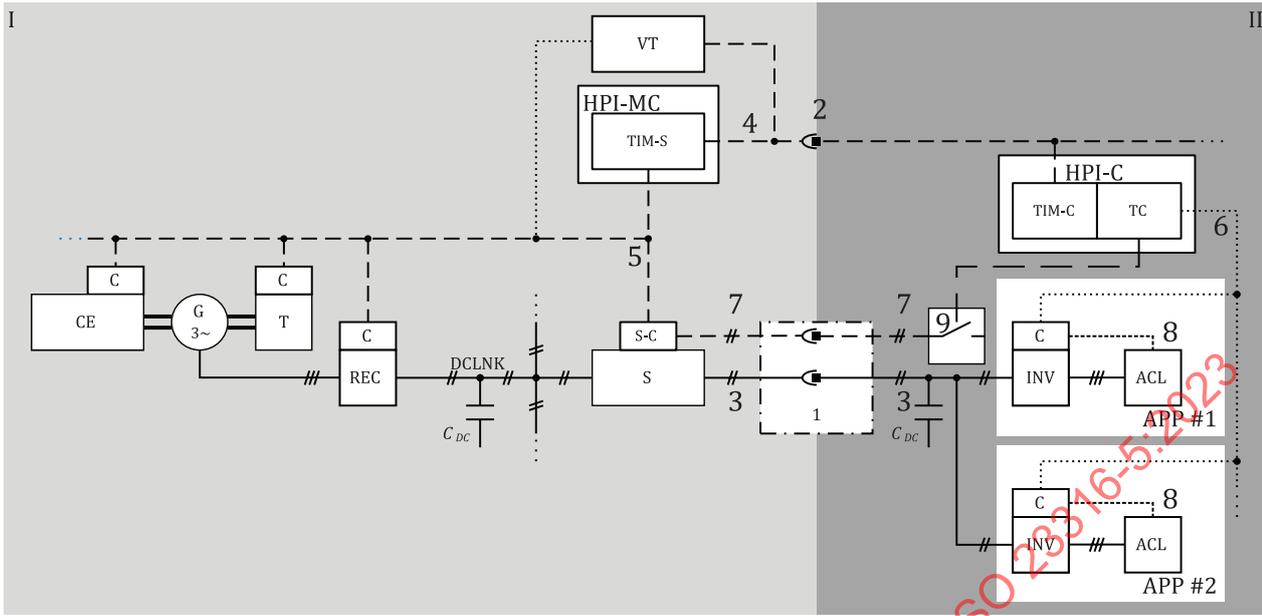
Key

ACL	AC load (e.g. electric motor)
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C	controller of a device
C_{DC}	DC link capacitor
CE	combustion engine
DCLNK	DC link
G	generator (as example of an electric power source)
HPI-C	high power interface - control
HPI-MC	High Power Interface - Master Control
INV	inverter (DC/AC converter)
L	load
REC	rectifier (AC/DC power converter)
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S-C	switch controller
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VT	virtual terminal (user interface, e.g. display)
I	supply system
II	consumer system
1	high power interface
2	ISOBUS connector
3	power lines
4	ISOBUS
5	supply system communication bus (e.g. tractor bus)
6	consumer system communication bus (e.g. implement bus)
7	interlock signal
8	feedback signal (by e.g. a sensor)

9   interlock signal line breaker

Figure 8 — General location of the pre-charge unit

NOTE 1   The supply system always provides at least a passive pre-charge unit. An additional pre-charge unit on a CS is an option.

NOTE 2   If electrolytic capacitors are used as DC link capacitance on the load, special handling due to their specific characteristics are given in B.2.

5.1.12.3   Functional requirement — Charge current

The maximum initial charging current shall not exceed 20 A. The maximum allowed current consumption of the load(s) during pre-charging over the DC link circuit shall not exceed 0,5 A.

If these conditions are not sufficient to charge the load(s) DC link circuit, the CS shall provide an autonomous pre-charge unit.

NOTE   If an electronic pre-charge unit is used, the initial current has AC and DC components. The current is calculated as RMS value over a time period of 100 ms.

5.1.12.4   Functional requirement — Autonomous pre-charge

If the value for the DC link capacitor (sent via communication according to ISO/FDIS 23316-6:—) is equal to zero, the supply system shall expect an autonomous pre-charging by the CS.

NOTE 1   In this case, the DC link voltage is switched on without initiating a pre-charge procedure from PS side.

NOTE 2   An example for a pre-charge state machine is shown in B.3.

5.2   DC link discharging procedure

5.2.1   General

After use or in case of faults (e.g. severing of the cable, unplugging during operation), the DC link capacitors are required to be discharged within a certain time period.

If the VC-B2 supply of the CS is interrupted, a function shall be provided on the CS to ensure a controlled capacitor discharge within the time limit defined in ISO 23316-3:2023, 5.5.3.1.

In the case of cable severing, the supply system shall switch off the HPI, and the CS shall discharge its own DC link capacitor and supply system shall de-energize the HPI.

5.2.2   Connection of MCS

5.2.2.1   General application

Combinations of front and rear CS as well as several rear combinations are commonly used. These applications shall be handled by the HPI to fulfil this requirement.

5.2.2.2   Interlock function

The interlock function is provided per HPI on one hand as a measure to check that connector and socket are plugged correctly and on the other hand to check, whether a reliable connection between CS and supply system is established.

NOTE 1   Internal interlock connections between VC-B2 devices on supply system or CS(s) are not considered.

NOTE 2   Because the source and evaluation units of the interlock signal are both on the side of the supply system, the manufacturer of the supply system can largely define the signal waveform and quality.
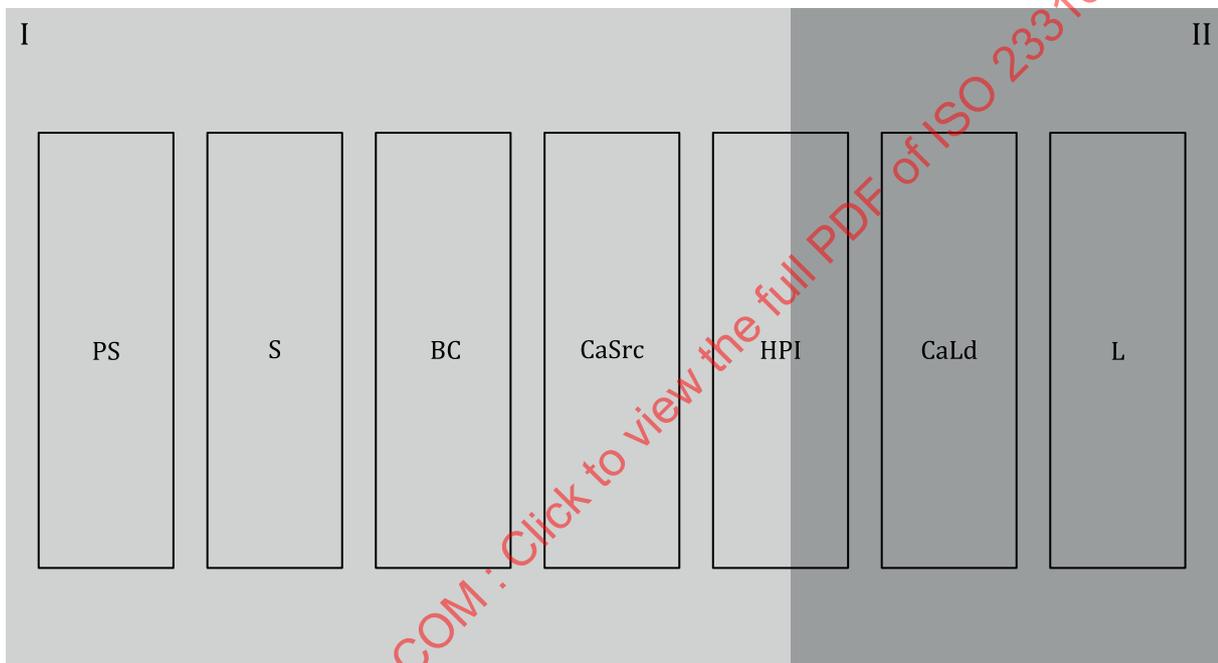
5.2.2.3   Pre-charge/discharge, disconnect

An individual pre-/discharge unit and disconnecting device shall be provided per HPI.

When multiple CSs are coupled in series connection, the "predecessor CS" shall serve as PS for the "follower CS", and therefore a "predecessor CS" shall provide the pre-charge function.

5.3   Compatibility criteria for PS, HPI and load

5.3.1   Block diagram

The main circuit blocks in the whole system are shown in Figure 9.

Key

BC   Brake chopper
CaLd   cable load
CaSrc   cable source
HPI   high power interface
L   load
S   pre-/discharge unit/(dis-) connecting device
PS   power source
I   supply system (e.g. tractor)
II   consumer system (e.g. implement)

Figure 9 — Electrical source and electrical load circuit blocks

5.3.2 Value ranges for system components:

To enable compatibility between supply system and CS, the following parameters shall be within these value ranges:

— inverter switching frequencies: 4 kHz < f < 16 kHz

— inverter switching frequency $f_{\text{switch-source}}$ - 3 * $f_{\text{fundmax-load}}$ > 4 kHz (if 6-step modulation mode is used).

— low pass filter for load inverters use a cut-off frequency $f_{\text{cutoff\_filter}} \sim$ 2 kHz (including complete DC harness, filter elements, and the DC link capacitor(s) on the load(s))

— PS 6-step mode is not allowed for PS (see below PSR2). The CS can use that mode. This avoids resonance effects.

— inner source impedance 1 mΩ < $R_{i\ src}$ < 175 mΩ

— inner source inductance $L_{i\ src}$: 50 μH (for $R_{i\ src}$ = 1 mΩ) < $L_{i\ src}$ < 8 mH (for $R_{i\ src}$ = 175 mΩ).

— DC link capacitance of one CS: 100 μF < $C_{DC\ src/ld}$ < 10 mF (approaches for a rough estimate: see Annex A)

— Y-capacitors: 100 pF< C_y < 1 μF (If no dedicated Y-capacitors are used, the parasitic capacitances are defining the lowest capacitance values)

— contact resistance DC-contacts according to ISO 23316-2:2023 4.5.7.

— resistance of the PBC (according to ISO 16230-1: <100 mΩ between two parts with connection through HPI included, which can be touched simultaneously by one person)

NOTE 1   In B.4 simplified electrical source and load circuit diagrams are provided, which are applicable to various operational modes. All device values correspond to the equivalent circuit diagrams.

NOTE 2   Cable length has no critical impact regarding the system behaviour (considerations regarding cable length, see B.1).

NOTE 3   Considerations regarding DC-Bus filters, see B.6.

5.3.3 Limitations on ripple current

Compatibility between PS and CS shall be ensured by the requirements according to Tables 2 and 3.

Table 2 — Requirements for PS (PSR)

Ref	Requirement	Rationale
PS Requirement 1 (PSR 1)	PS shall use an active PWM rectifier to provide the DC bus source.	It is required to be known if a PWM rectifier is in use, as it will define what current rating can be expected in the DC capacitor bank.
PS Requirement 2 (PSR 2)	PS PWM rectifier shall not use bus clamp modulation, over-modulation or 6 step modulation.	Use of any of these modulation methods would produce low frequency current ripple on the DC bus which can overload the load(s).
PS Requirement 3 (PSR 3)	The PS shall be able to continuously carry an AC ripple current which originates in the load(s). Frequency band 10 Hz to 100 kHz Magnitude I_{lf} I_{lf} =0,17 I_{dc} Where I_{dc} is the rated dc bus current of the PS.	This level of ripple current is likely to flow in the system. It does not significantly affect the PS DC bus capacitor life time or temperature or cause excessive ripple current. Low frequency filter (f< 1 kHz) would degrade transient performance of the dc bus voltage.

Table 3 — Requirements for load (ELR)

Ref	Requirement	Rationale
Load Requirement 1 (ELR 1)	If the load uses inverters, which operate with PWM modulation, the ripple current, which flows in the PS, shall be limited.	Lower power loads produce a PWM band ripple current which is low enough to have little effect on the PS.
	Passive LC filters in the load may be used to reduce this current.	These CS(s) do not need a filter. CS(s), which would exceed the allowed ripple current need to have a series inductor to limit the current.
	Frequency band 1 kHz to 100 kHz	
	Magnitude I_{lf} $I_{lf}=0{,}17\ I_{dc}$	
	I_{dc} is the rated dc bus current of the PS.	
	The CS shall specify minimum PS current, which allows the operation of the CS.	
	Current shall be measured using test ELT1 (see below 5.3.4.2).	
Load Requirement 2 (ELR 2)	If the load uses inverters, which operate with 6-step, bus clamp or over-modulation, the ripple current, which flows in the PS, shall be limited.	Lower power load(s) produce a low frequency band ripple current which is low enough to have little effect on the PS from a thermal or voltage ripple perspective.
	Passive LC filters in the load may not be used to reduce this current.	
	Frequency band 10 Hz to 1 kHz	
	Magnitude I_{lf} $I_{lf}=0{,}17\ I_{dc}$	
	I_{dc} is the rated dc bus current of the PS.	
	Current shall be measured using test ELT1 (see below 5.3.4.2).	
Load Requirement 3 (ELR 3)	The total ripple current limits from ELR1 and ELR2 shall not be exceeded	The whole frequency band needs to be considered.
	Frequency band 10 Hz to 100 kHz	
	Magnitude I_{lf} $I_{lf}=0{,}17\ I_{dc}$	
	I_{dc} is the rated dc bus current of the PS.	
	Current shall be measured using test ELT1 (see 5.3.4.2).	

5.3.4 Test methods

5.3.4.1 PS tests (PST)

a) Test1 (PST1): ripple voltage

Load the PS to the rated output current using a resistive load with a series inductance of > 250 μH.

Measure the ripple voltage at the PS terminals.

PS ripple voltage shall not exceed 2 % of VC-B2 DC voltage in the DC link circuit.

b) Test 2 (PST2): ripple current

Load the PS to the rated output current I_{DCmax} (i.e. the maximum output current of the PS) using a resistive load with a series inductance of > 250 μH. The test is performed with 3 frequencies of the current I_{DCmax}:

— Frequency 100 Hz

— Frequency 1 kHz

— Frequency 10 kHz

Allow the system to operate until an electrical and thermal steady state is reached.

The total ripple current of $I_{ripple} = 0{,}17 * I_{DC}$ shall not be exceeded under any test frequency.

The PS manufacturer shall both identify and test a sufficient number of test points to guarantee the full range for the design (This condition is valid only for the initial PS in the system).

5.3.4.2   Load tests (ELT)

Test (ELT1): ripple current (see Figure 10)
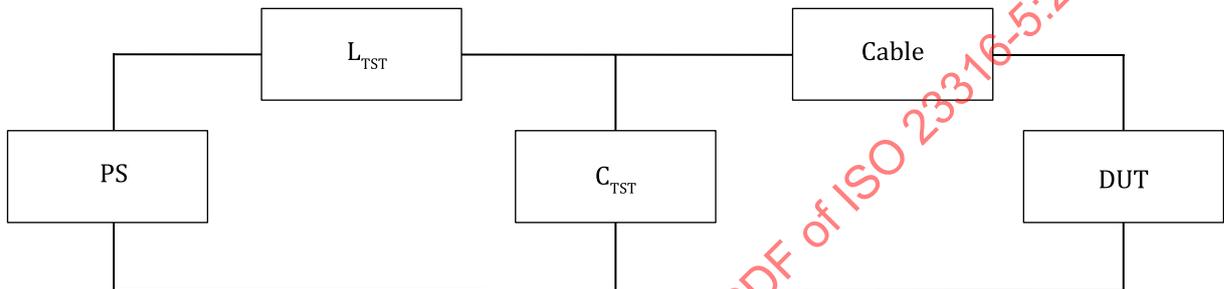
Key

Cable	cable (length 5 m)
C_{TST}	test capacitor (10 mF)
DUT	device under test
L_{TST}	test inductor (250 µH)
PS	power source

Figure 10 — Ripple current test circuit

Test procedure:

— Connect the DUT as shown above

— Load the DUT to its rated loading

— Measure the current in the test capacitor.

The total ripple current of $I_{ripple} = 0{,}17 * I_{DC}$ shall not be exceeded (This condition is valid only for the first CS in the system).

5.3.5   Ripple current in case of MCS

5.3.5.1   Series connection of CSs

A series connection of CS (predecessor CS supplies following CS) shall not exceed the ripple current limitation of $I_{ripple} = 0{,}17 * I_{DC}$ of the total connected load.

5.3.5.2   Other CS combinations (e.g. front –rear)

In this case, each CS shall not exceed $I_{ripple} = 0{,}17 * I_{DC}$ of its maximum rated current.

NOTE 1   If the rated current of the connected load exceeds the rated current of the PS, the DC link capacitor of the PS can be overloaded.

NOTE 2   Online measurement of ripple currents (harmonic percentage of the overall current) is difficult. Hence, the PS might not be able to measure the ripple current during operation in order to signal the load to reduce its request in case of overload.

NOTE 3   PS rated power < power request of load(s) AND, simultaneously, special modulation methods on the specific load(s) are in use.

NOTE 4   Measurement of DC link capacitor temperature of the PS is complex (sensors have to be placed at the "hot spots").

5.3.6   Limited operation of source-load(s) combinations with respect to ripple currents

5.3.6.1   Ripple currents exceed allowed values before operation (result of parameter interchange)

The CS(s) shall provide characteristic maps, specifying under which load conditions the supply system ripple current limitation will not be exceeded. This may result in a torque reduction of drive systems. The information helps to determine, whether operation is possible. In this case, the operator should decide whether operation is possible with certain limitations (reduced speed or torque, reduced ground speed of the supply system, etc.). If operation is possible, the operator should adjust the whole system according to his experience.

5.3.6.2   Overload situation during operation

In case of an overload situation during operation, the operator and the CS(s) shall be informed by the supply system. In this case, countermeasures should be taken in order to reduce the consumption of the load. If there is no reaction, the supply system shall turn off the load to prevent PS from damage.

Communication parameters (ripple current capacity/requirement of electrical source and loads) shall be transferred as part of the initialization procedure (see ISO/FDIS 23316-6:—).

5.3.7   Energy feedback

Depending on operational conditions, additional energy is provided into the system, which leads to an increase of the DC voltage in the DC link. In order to protect connected components against overvoltage damage, the following defines how to handle with the two cases.

— Surplus energy generated by the load due to dynamic effects (e.g. braking, load dump) shall be taken over by the PS. The PS takes measures to stabilize the DC voltage (e.g. brake chopper, feeding back energy to engine).

— CS(s), which are able to generate energy over a longer period of time (e.g. driven axles during downhill drive), take measures on their own to keep the voltage under the permitted maximum ("longer" period of time is defined according to "energy over time diagram" (see Figure 11).

5.3.8 Functional requirements — Energy feedback over time

Key

rmp   rated maximum power in % (related to PS)

t   time in seconds
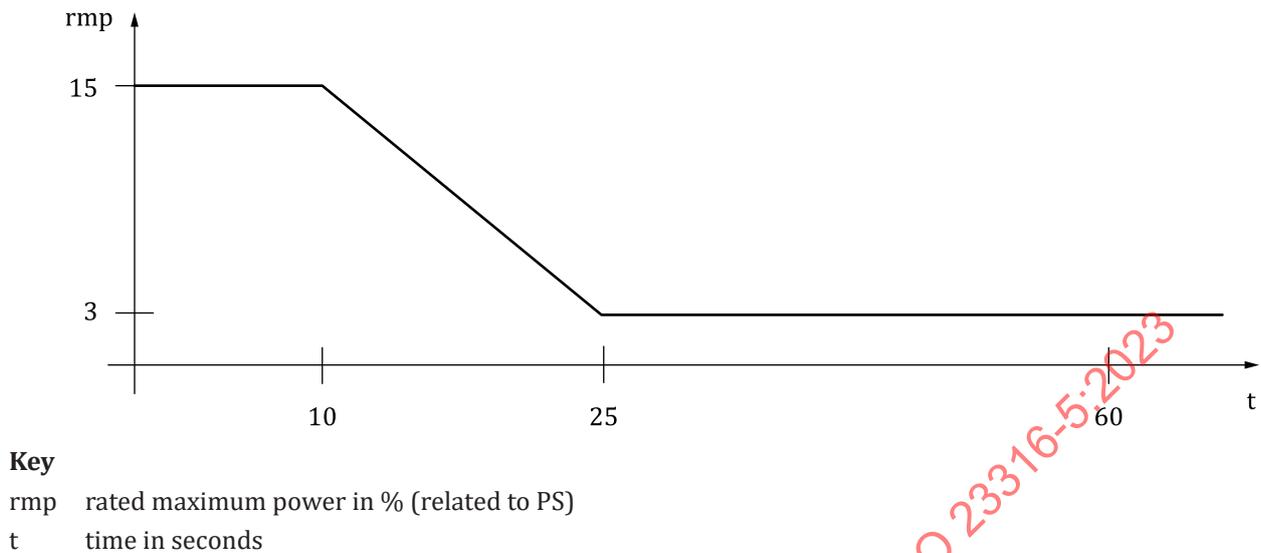
Figure 11 — Source energy feedback requirements

The power-over-time curve defines the minimum energy the PS shall absorb as feedback by the load. The curve has three sections:

a) Section 1: For the first 10 s the PS shall absorb at least 15 % of its rated maximum power.

b) Section 2: The PS energy absorption shall decrease linearly over time to the value in section 3 (time period 10 s < t < 25 s). Calculation in this time interval: rmp = -0,8*t+23 [%].

c) Section 3: After transition of the first two sections, 3 % of the rated maximum power shall be absorbed by the PS continuously.

The values as defined above shall be the minimum of the PS. If the PS is able to absorb more energy, it shall be communicated according to ISO/FDIS 23316-6:— (negative rated current).

In case of an overload situation during operation, the operator is informed to take appropriate measures in order to reduce the consumption of the CS(s). If there is no reaction by the operator, the PS can turn off the supply of the CS(s) to prevent from damage.

5.4 Overload protection

De-rating on the CS side prevents from a sudden shutdown and helps to realize an optimized system solution for different supply systems and CS(s).

According to 5.1.8.4 a supply system shall provide an electronic overcurrent protection.

For maximum performance under changing load conditions, a dynamic de-rating depending on the present system state should be provided.

NOTE   As an example, the i^2t-value method is presented in Annex B.

When MCS are in operation, the HPI-MC shall be responsible for the communication in accordance ISO/FDIS 23316-6:— for system handshake and initialization. In addition, the HPI-MC shall manage the priority of different loads of the multiple implements in cases of any load current restriction.

Annex A
(informative)

Estimation methods for DC link film capacitors

A.1 General

The following calculation methods are rough estimations for the size of a DC link capacitance. See Formulae (A.1) and (A.2).

A.2 Minimum DC link system capacitance

See Reference [6].

$$\Delta W = \int_0^{T_p} \left[P_{in}(t) - P_{out}(t) \right] dt \approx C_d \cdot U_d \cdot \Delta U_d \tag{A.1}$$

ΔW   is the energy variation within switching period (T_p);

P_{in} is the input power;

P_{out} is the output power;

U_d is the DC link voltage;

C_d is the DC link capacitance.

A.3 Minimum DC link capacitance (film capacitors)

$$C_{d,min} = \frac{\Delta P_{max} \cdot T_p}{2 \cdot U_d \cdot \Delta U_{d,max}} \tag{A.2}$$

ΔP_{max} is the maximum power change within switching period (T_p);

U_d is the DC link voltage;

T_p is the switching period;

$\Delta U_{d,max}$ is the maximum DC link voltage variation (maximum ripple);

C_d is the DC link capacitance.

A.4 Minimum DC link capacitance — Alternative calculation method — General assumptions

a) Three-phase voltage source converter (VSC)

— space vector modulation (SVM)

— DC bus current is zero or a sum of phase currents depending on inverter switching state

— total capacitor RMS current is approximately 0,6 times the motor current

b) Motor phase current is approx. 2 A per kW

— Using 450 V AC motors designed for a 700 V DC bus

— Applies to motors from 1 kW to 100 kW (±10 % change)

— Based on efficiency and power factor and rated voltage

    — DC cap current = 0,6 x 2 A/kW = 1,2 A/kW

    — DC capacitance using mA/µF values

— Film caps 4 µF/kW to 12 µF/kW

— Al elec. caps 40 µF/kW to 120 µF/kW

c) Worst case at m=0,5 and peak current I_{pk} and f_{sw} min

— $C_{DC}*\Delta U = I_{pk}/4*f_{sw}$

— $C_{DC} = I_{pk}/4*\Delta U *f_{sw}$

— $I_{pk} = \sqrt{2}*I_{rms}$

— $I_{pk} = \sqrt{2}*2*I_{rms}$

— Based on 2 A/kW

— Allow 5 % pk-pk at PWM frequency

— ΔU = 35 V

— $f_{sw\ min}$ = 2 kHz

— $C_{DC\ min} = \sqrt{2}*2*In/(4*35\ V*2\ kHz)$

— $C_{DC\ min}$ = 10 µF per kW

Annex B
(informative)

Technical details

B.1 Calculation of cable inductance
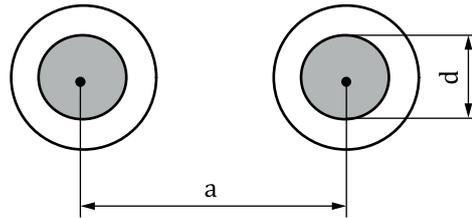
Key

a   cable distance

d   conductor diameter

Figure B.1 — DC conductor arrangement

$$L' = \frac{\mu_0 \cdot \mu_r}{\pi} \cdot ln\left(\frac{2 \cdot a}{d}\right) = \frac{\mu_0 \cdot \mu_r}{\pi} \cdot ln\left(a \cdot \sqrt{\frac{k_f \cdot \pi}{A}}\right) \qquad (B.1)$$

$$a_{min} = 2 \cdot \left(\sqrt{\frac{A}{k_f \cdot \pi}} + s_i\right) \qquad (B.2)$$

Vacuum permeability	$\mu_0 =$	$4\pi \cdot 10^{-7}$	[Vs / Am]
Permeability copper	$\mu_r =$	1	
Filling factor	$k_f =$	0,9	
Cable cross section	$A =$	50; 70; 90	[mm^2]
Isolation thickness	$s_i \cong$	4	[mm]

Table B.1 — Example values

A mm^2	a mm	L' H/m
50	16,4	545E-9
50	30	786E-9
50	60	1,1E-6
50	90	1,2E-6
70	18,0	513E-9
70	30	719E-9
70	60	996E-9
70	90	1,2E-6

Table B.1 *(continued)*

A	a	L'
mm^2	mm	H/m
90	19,3	492E-9
90	30	668E-9
90	60	946E-9
90	90	1,1E-6

Table B.1 shows the dependency on cable cross section and distance of the (parallel) assembled cables.

NOTE   In the calculations as shown in Formulae (B.1) and (B.2), the inner inductance per unit length is not considered. A potential consideration of the inner inductance does not influence further conclusions.

B.2   Reforming of electrolytic capacitors

If electrolytic capacitors are not used for a long time period (e.g. greater than one year), a "soft reactivation", i.e. reforming procedure needs to be considered. Reforming requires the capacitor to be recharged with reduced current dependent upon:

— capacitor type;

— overall DC –link capacitance value;

— duration of inactive period and storage temperature;

— manufacturer instructions for reforming.

The reforming procedure is not intended to be performed by the PS or by its pre-charge device. Thus, the CS is responsible for capacitor reforming.

NOTE   Manufacturer recommendations for reforming vary over a wide range, thus different charging modes (gentle/fast) are needed depending on the capacitor technology used.
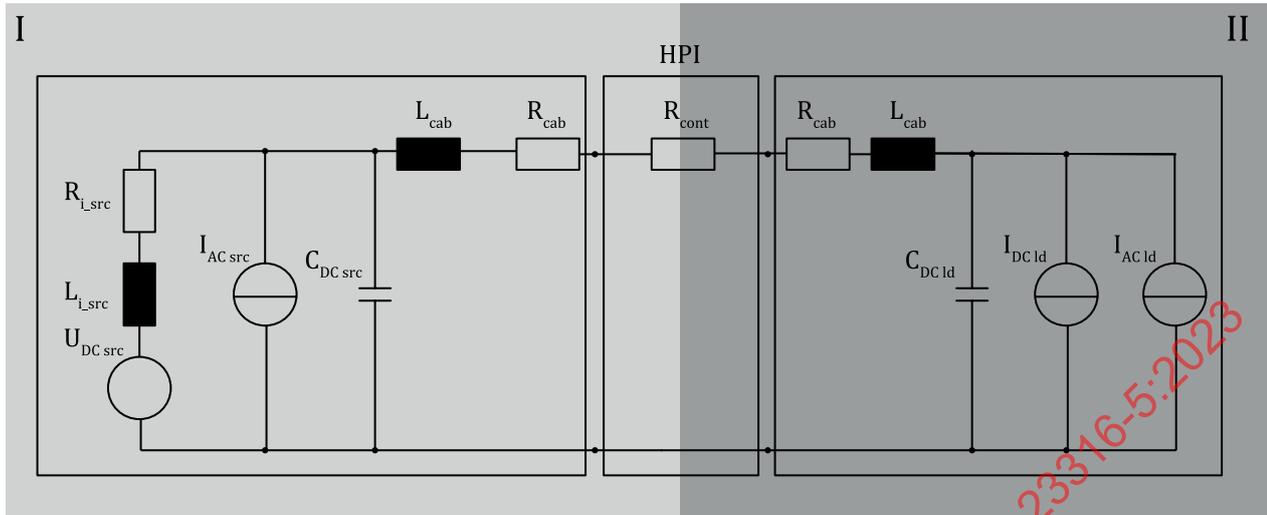
A stepwise charging (25 %, 50 %, 100 %) with a check of voltage symmetry after each step can be followed to detect a requirement for reforming, although this increases the system complexity.

If the capacitors are deeply discharged, then specialised workshop services may be required.

B.3   Simplified circuit diagrams describing various operational modes

NOTE   Coverage of the circuit diagrams < 100 kHz (approximate factor 6 of max. switching frequency).

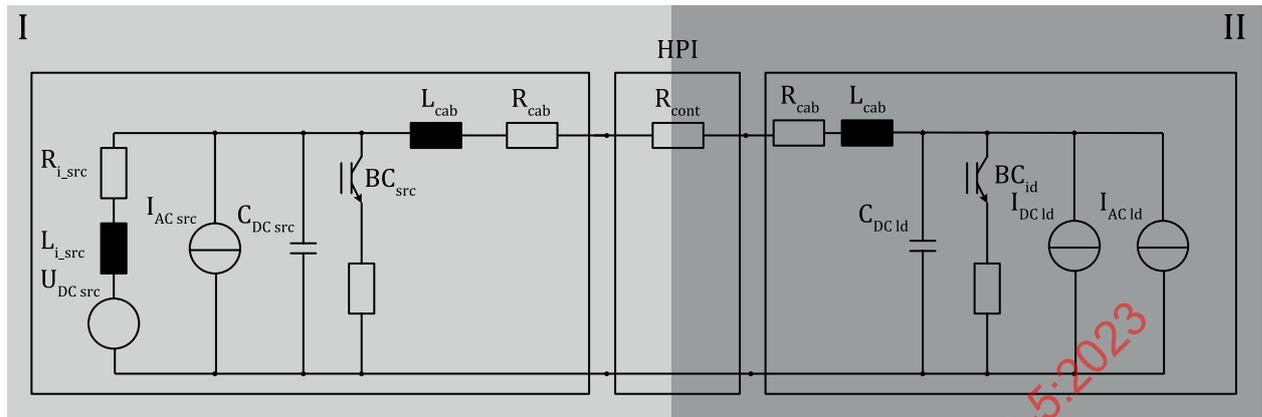## B.3.1   Normal operation (connected, no energy feedback)

Key

$C_{DC\ src}$	DC link capacitance source
$C_{DC\ ld}$	DC link capacitance load
II	consumer system (e.g. implement)
I	supply system (e.g. tractor)
HPI	high power interface
$I_{AC\ src}$	AC current source
$I_{AC\ ld}$	AC current load
$I_{DC\ ld}$	DC current load
L_{cab}	cable inductance
$L_{i\ src}$	inner source inductance
$R_{i\ src}$	inner source resistance
R_{cab}	cable resistance
R_{cont}	contact resistance
$U_{DC\ src}$	DC voltage source

Figure B.2 — Normal operation circuit

NOTE   An inverter can, in some cases, behave like a negative impedance such that the current increases when the voltage falls.

Use the combination of inner source impedance $R_{i\ src}$ + $L_{i\ src}$ and virtual current source $I_{AC\ src}$ to model the ripple current at the terminals of the socket As a consequence of the ripple current, ripple voltage becomes present at the connector terminals.

B.3.2 Operation with energy feedback by CS

Key

BC$_{src}$	brake chopper source
BC$_{LD}$	brake chopper load
C$_{DC\ src}$	DC link capacitance source
C$_{DC\ ld}$	DC link capacitance load
II	consumer system (e.g. implement)
I	supply system (e.g. tractor)
HPI	high power interface
I$_{AC\ src}$	AC current source
I$_{AC\ ld}$	AC current load
I$_{DC\ ld}$	DC current load
L$_{cab}$	cable inductance
L$_{i\ src}$	inner source inductance
R$_{i\ src}$	inner source resistance
R$_{cab}$	cable resistance
R$_{cont}$	contact resistance
U$_{DC\ src}$	DC voltage source

Figure B.3 — Operation with energy feedback circuit

The brake chopper (BC) on the supply system and CS sides is optional.
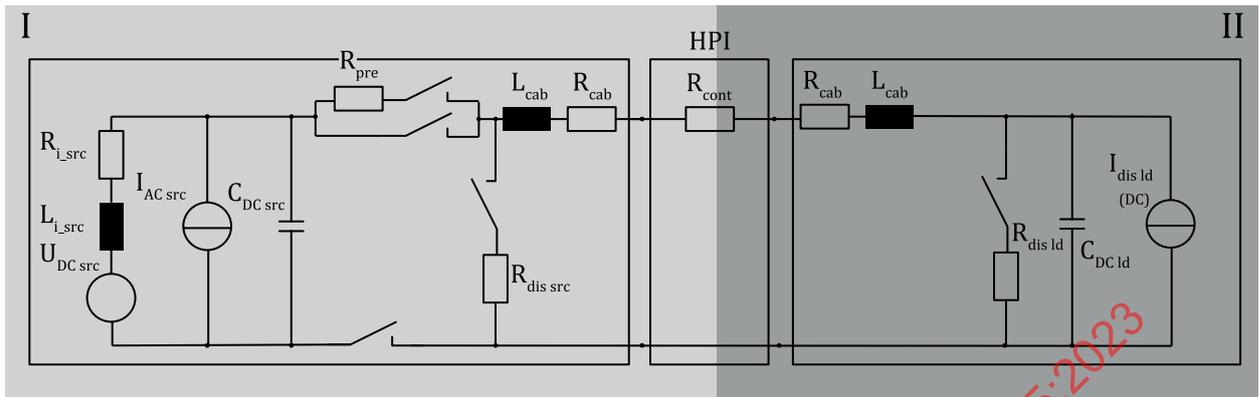
B.3.3   Pre-charge operation
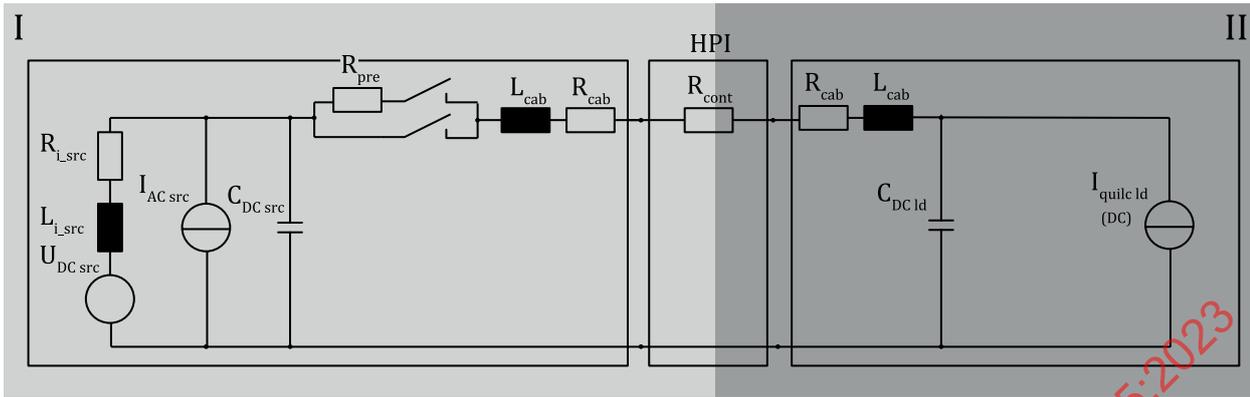
Key

$C_{DC\ src}$	DC link capacitance source
$C_{DC\ ld}$	DC link capacitance load
II	consumer system (e.g. implement)
I	supply system (e.g. tractor)
HPI	high power interface
$I_{AC\ src}$	AC current source
$I_{quilc\ ld\ (DC)}$	DC quiescent current load
L_{cab}	cable inductance
$L_{i\ src}$	inner source inductance
$R_{i\ src}$	inner source resistance
R_{cab}	cable resistance
R_{cont}	contact resistance
R_{pre}	pre-charge resistor
$U_{DC\ src}$	DC voltage source

Figure B.4 — Pre-charge operation circuit

— The load power consumer is modelled by a quiescent current source (max. allowed quiescent current according to 5.1.12.2).

— Pre-charge unit and bypass current path is modelled in the diagram.

— Consider optional pre-charge device on the CS (see "pre-charge procedure").

B.3.4 "Normal" discharge operation (No emergency discharge)

Key

$C_{DC\ src}$	DC link capacitance source
$C_{DC\ ld}$	DC link capacitance load
II	consumer system (e.g. implement)
I	supply system (e.g. tractor)
HPI	high power interface
$I_{AC\ src}$	AC current source
$I_{dis\ ld\ (DC)}$	DC discharge current load
L_{cab}	cable inductance
$L_{i\ src}$	inner source inductance
$R_{i\ src}$	inner source resistance
R_{cab}	cable resistance
R_{cont}	contact resistance
$R_{dis\ src}$	discharge resistor source
$R_{dis\ ld}$	discharge resistor load
R_{pre}	pre-charge resistor
$U_{DC\ src}$	DC voltage source

Figure B.5 — Discharge operation circuit

— Connect/Disconnect unit considered.

— The installation of a discharge device on the CS depends on functional and safety related considerations of the respective CS (e. g. implement) manufacturer (see ISO 23316-3).