Particular Requirements on Drive Inverters for Safe and Robust Operation on an Open Industrial DC Grid

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Abstract

Today DC offers far-reaching advantages over AC. Therefore, many devices have been equipped with an internal DC link for years. In the field of energy supply, the use of DC technology is also growing and is state of the art e.g. in offshore, high-voltage, automotive and data center applications. The spread of industrial open DC grids is currently starting and is completely different due to the requirements: The DC grid itself and energy flows in an industrial environment are highly dynamic and bidirectional. Due to the low impedance electrical connection of the DC links of many devices, stored energies in fault cases as well as ripple currents during operation place particular requirements on the devices.

Introduction

DC grids offer a series of advantages in the industrial sector, especially for voltage source inverter-based electric drives. For this reason, proprietary DC grids in the cabinet have been state of the art for many years. Hence there is a need for extended, open DC grids in the industrial environment. The elimination of the rectifier and the direct electrical coupling makes it possible to exchange energy, e.g. generative

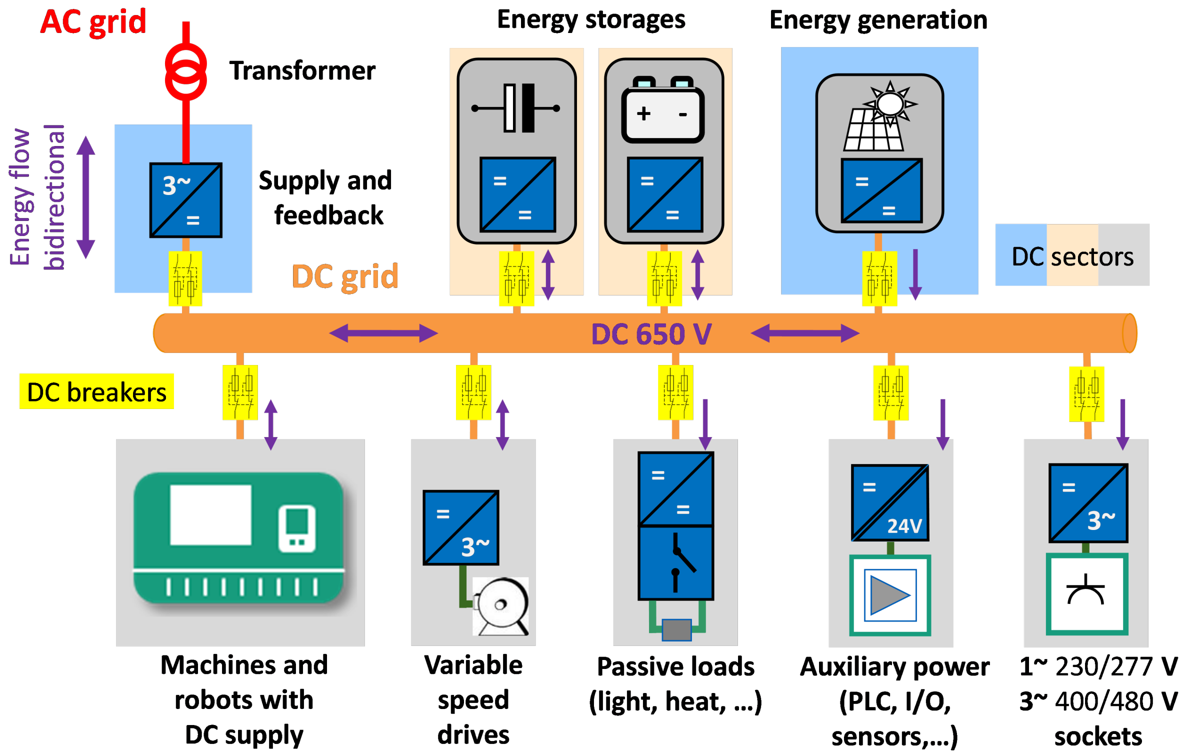

Fig. 1: Concept for an open industrial DC grid [2]

energy of drives in braking operation. Consequently braking resistors can be completely eliminated and 20 - 30 % energy can be saved. The potential savings increase significantly during intermittent operation, for example in intralogistics for storage and retrieval machines or industrial robots with short and fast accelerations and decelerations [1].

Due to the fact that devices - especially electrical drives - in industrial environments often operate very dynamically and the flow of electrical power is correspondingly highly dynamic, the DC grid itself must also offer a high degree of dynamics. In relation to the nominal power of the DC grid, this results in a high capacity and low inductance, which also causes the short-circuit power to increase dramatically in the event of a fault [3] and transient overvoltages to reach high maximum levels [4]. Furthermore, due to the low impedance connection of the DC links of the devices, ripple currents can flow between individual devices and additionally load them. Devices must be designed for these grid-side influences to ensure safe and robust operation for the intended lifetime.

Concept for an Open Industrial DC Grid

The concept of DC-INDUSTRIE [2] is to connect industrial devices, such as electric drives, to each other via an open DC grid. The AC/DC conversion, which is always necessary with controlled industrial drives, can be carried out at a central point to the AC grid. By eliminating the need for uncontrolled rectifiers, the overall efficiency of plants can be increased and the emitted disturbance of harmonics significantly reduced. A further advantage of DC grids is the easy coupling of storage units and decentralized energy generators, such as photovoltaic systems. If the DC grid is controlled with intelligent grid management, it can react flexibly to grid voltage changes and failures. This increases the availability of the plants. The idea of DC-INDUSTRIE is to integrate devices for dedicated machine functions in load sectors. Each load sector is connected to the DC grid with a DC connection box. The task of the DC connection box is to protect all devices within the load sector from disturbances in the DC grid (overcurrent, over- and undervoltage) and to disconnect the load sector from the DC grid in case of short circuit faults etc. in the inner circle. For this task, very fast DC switches in semiconductor- or hybrid-technology are needed [5].

Infeed sections are managed as single load sectors. The DC grid can be operated at a star point grounded AC transformer or designed as an isolated DC grid (typically with an Active Infeed Controller).

Fig. 1 illustrates the concept as an overview. In addition to drive inverters (centralized or decentralized) and power supply units for coupling to the AC grid, innovative switching and protective devices as well as electromagnetic compatibility (EMC) input filters are required.

Grid-side Influences on Devices

In the industrial environment, devices are exposed to many influences that can affect their lifetime or function. While environmental influences are limited by appropriate housings or mounting locations, for example, electrical influences from the mains supply must also be limited. This is necessary so that the expected lifespan is maintained and the function is ensured - i.e. a device functions safely and robustly on the DC grid. The devices in the industrial DC grid are usually very similar in design, see Fig. 2. The most important components, regardless of the type of converter, are

- an input filter (inductance),
- a DC link (capacitance),
- and a power output stage (semiconductor-based switches).

The capacitances in the DC link, which are usually electrolytic capacitors in drive inverters, age over time [6]. Semiconductor-based switches, on the other hand, whether IGBT, SiC, etc., fail abruptly in the event of overload [7].

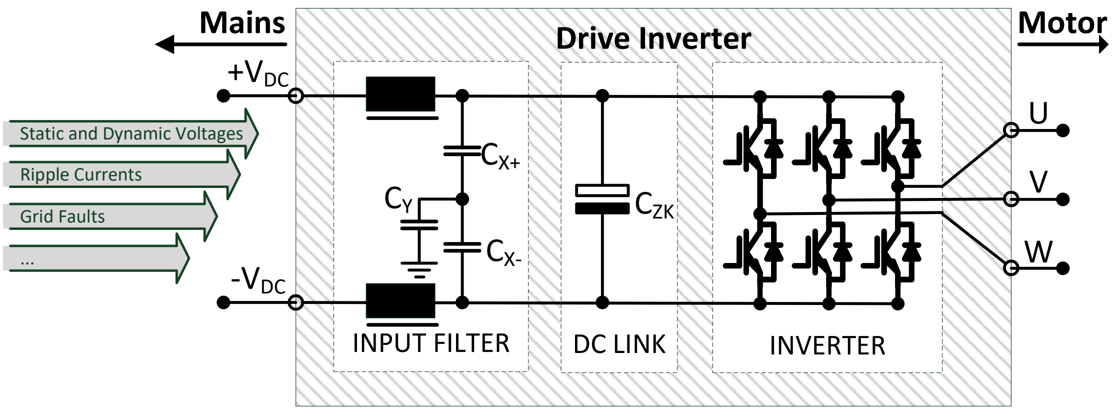

Fig. 2: Grid-side Influences on Devices and a symbolized Drive Inverter with its main components: Input Filter, DC Link and Inverter (left to right)

The most important electrical influences from the grid are:

- Voltage ranges, especially transient overvoltages [8]
- Ripple currents between individual devices [9]
- Device and grid faults [10]

Requirements on Drive Inverters for Safe and Robust Operation

To ensure that devices function safely and robustly when operated in the DC grid, the possible influences mentioned before must not lead to any significant impairments. If the influences and the devices are matched to each other, this can be ensured.

Voltage: Ranges and Transient Overvoltages

The voltage with which the devices are supplied is the decisive factor in the selection of components. A distinction must be made between the supply voltage, which is comparatively static and lies within

Table I: Specified static (right column S4) and dynamic voltage ranges (columns S1 to S3b) [2]

Upper voltage limit Ux for nominal voltage 540 V / 650 V	**Voltage band**	***S1:*** ***t* < 100 µs**	**S2: 100 µs ≤ *t* ≤ 1 ms**	**S3a: 1 ms ≤ *t* ≤ 5 s**	**S3b: 5 s ≤ *t* ≤ 60 s**	**S4: t > 60 s**
U6: 1500 V	B7	A7				
U5: 1200 V	B6	A6	A7			
U4: 880 V	B5	A6	A7	A7	A7	
U3b: 800 V	B4	A4	A5	A5	A7	A7
U3a: 750 V	B3h	A3	A3	A3	A4	A5
U2: 485 / 600 V	B3l	A3	A3	A3	A3	A3
U1: 400 V	B2	A4	A4	A2	A2	A1
	B1	A4	A2	A1	A1	

Voltage ↑ Time →

fixed limits, and possible transient overvoltages as well as undervoltages. The reason for this is that different components have different sensitivities. Capacitors, especially electrolytic capacitors, are comparatively robust to transient overvoltages. In other words, voltages that exceed the supply voltage for a few microseconds by a factor of up to two do not necessarily lead to damage. This is mainly due to their parasitic properties, such as the R_{ESR}, R_{Leak} and L_{ESL}, and their ability to absorb energy. Semiconductors, on the other hand, cannot handle overvoltages beyond their rated voltage. In the case of 1200 V rated types used in industrial applications, even slight voltages in addition to this lead to a defect [7]. Static voltages, i.e. voltages that are permanently present, have comparatively little effect on semiconductors. On the other hand, too small voltages lead to increased currents in order to provide the desired power for e.g. a drive. The increased currents lead to further heating in all components involved. In particular, the semiconductors with their small thermal capacity can be overloaded and fail.

Table I shows in detail possible voltages in relation to the time for which they can be present. In the right column S4 : t $>$ 60 s, the voltages and voltage limits that are permanent are indicated:

- $>$ 800 V: Overvoltage (with active protection)
- 750 V to 800 V: Overvoltage (without active protection)
- 485 V to 750 V: Normal working voltage
- $<$ 485 V: Undervoltage

Since transient voltages can also occur in a grid, caused for example by load changes, these are considered normal operating conditions. Accordingly, devices that are operated on the grid must also withstand voltages exceeding their nominal values without negative influence. Table I lists ranges for smaller time intervals in the remaining columns from right to left. Column S1 : t $<$ 100 µs, for example, indicates that voltages up to 1500 V for less than 100 µs are allowed in principle and must be assumed to exist. In order to avoid damage to devices influenced by voltages, they must be designed and components dimensioned accordingly. An inductive component in the input filter in combination with a capacitive DC link capacitor, for example, forms a low-pass filter which can prevent a high, but only short-acting transient overvoltage from affecting semiconductors.

Fig. 3 illustrates an example of transient voltage events triggered by the switching off of a simple load in the DC grid. Even under real conditions, the maximum value of the voltage can easily reach twice the initial value. On the other hand, this example also shows the time frame in which the event and thus a potential danger is over again: In about 10 µs after the switch-off event, the voltage has reached the initial value again.

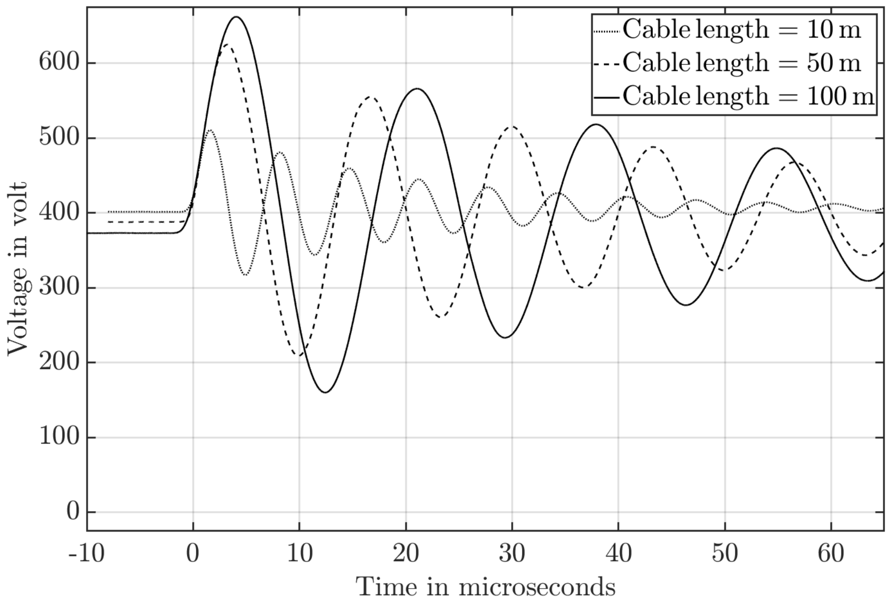

Fig. 3: Measurement of overvoltage events due to a Load Dump with variations in cable length

Ripple Currents between Individual Devices

Due to the fact that the devices are operated on the open industrial DC grid without an input rectifier on the grid (see Fig. 2), equalizing currents can occur between the devices. Only the input filters of the devices and the cable connections separate the individual DC links from each other. A device with a high AC current ratio in the DC link can serve itself on the DC link of another device. In this case, the other device is additionally stressed and can be overloaded if the ripple current is too high. The result is premature aging of a device forced by the mains side.

In order not to overload the components of individual devices, they must be able to handle a mutual ripple current load. This is because these currents cannot be completely avoided. In the case of the DC system concept, there is an agreement that each device has a minimum DC link capacitance: $C_{ZK} \geq 25\,\mu F/kW$. This ensures, on the one hand, that devices emit only limited amounts and, on the other hand, what devices must be able to withstand. A possible solution may also be to connect external capacitors to the DC grid at certain points, e.g. on a rail system for mobile equipment [11].

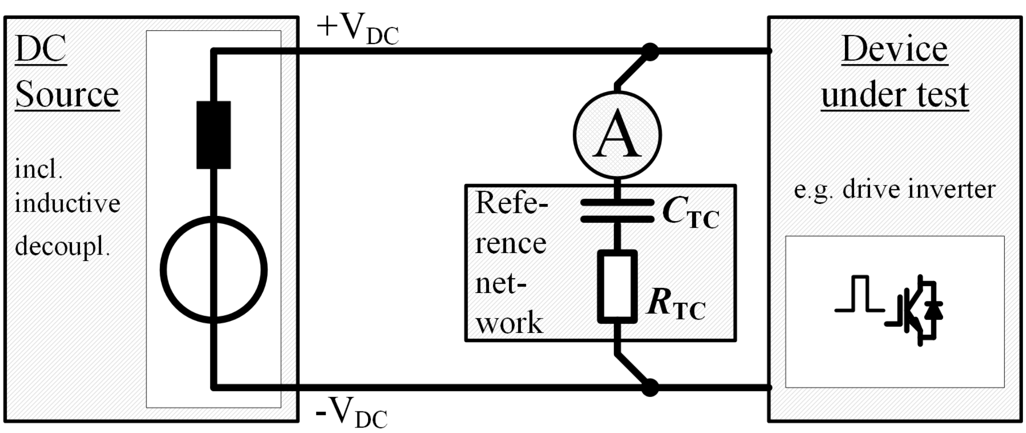

Fig. 4: Ripple current measurement method

Increased ripple currents emanate in particular from devices which use film capacitors as DC link storage.

Due to their increased resistance to ripple current loads, these can be designed smaller in the individual device. For operation in a combined system, on the other hand, the use of such a device means a load on other devices in the system.

To detect a potential overload of electrolytic capacitors, a simple measuring method can be used. Fig. 4 shows the basic setup. Using a simple multimeter, the RMS current is measured that flows into a series circuit of film capacitor and resistor. This circuit is inserted into the DC grid at $+V_{\mathrm{DC}}$ and $-V_{\mathrm{DC}}$ and can test both individual devices and devices in a combination. With an appropriate design, the circuit emulates the impedance of a real DC link electrolytic capacitor and does not influence the devices due to comparatively small values. With a capacitance of $C_{\mathrm{TC}} = 1\,\mu\mathrm{F}$ and a resistance of $R_{\mathrm{TC}} = 20\,\Omega$, the maximum current is $I_{\mathrm{RMS}} = 40\,\mathrm{mA}$ for individual devices and $I_{\mathrm{RMS}} = 28\,\mathrm{mA}$ for devices in combination.

Capacitors play a special role when considering possible loads due to ripple currents, which, unlike other influences, can be permanent and unnoticeable during operation. And in the lifetime, these are a significant part.

The resulting lifetime L_{X} of an electrolytic capacitor can be calculated by:

$$L_X = L_0 \cdot 2^{\frac{T_0-T_a}{10k}} \cdot K_i^{\left(1-\left(\frac{I_a}{I_0}\right)^2\right)\cdot\frac{\Delta T_0}{10K}} \cdot \left(\frac{U_0}{U_a}\right)^n \qquad (1)$$

Each individual factor is based on heat generation.

The single factors of equation (1) are:

L_0	Nominal lifetime
$2^{\frac{T_0-T_a}{10k}}$	Temperature factor
$K_i^{\left(1-\left(\frac{I_a}{I_0}\right)^2\right)\cdot\frac{\Delta T_0}{10K}}$	Ripple current factor
$\left(\frac{U_0}{U_a}\right)^n$	Voltage factor

Table II: Parameters for the lifetime calculation equation (1)

L_{X}	resulting lifetime	L_0	nominal lifetime	K_{i}	safety factor (2 - 4)
I_{a}	actual ripple current	I_0	nominal ripple current	n	exponent (3 - 5)
T_{a}	actual ambient temp.	T_0	nominal temperature	ΔT_0	overtemp. core (5 - 10 K)
U_{a}	actual voltage	U_0	rated voltage		

The ripple currents include a wide range of frequencies. Mainly these are multiples of the semiconductor switching frequency, which is 4 kHz, 8 kHz or sometimes 16 kHz with IGBTs today. These multiples must be taken into account with regard to the frequency F_{x} and the amplitude I_{x} in the equation (2). In this case, I_a is the frequency-weighted equivalent ripple current, which is calculated as follows:

$$I_a = \sqrt{\left(\frac{I_1}{F_1}\right)^2 + \left(\frac{I_2}{F_2}\right)^2 + \ldots + \left(\frac{I_n}{F_n}\right)^2} \qquad (2)$$

In general, it can be stated that the lifetime of capacitors is greater when they are operated in the DC grid than in the AC grid. This is due in particular to the fact that the rectifier's recharging currents are not present.

Device and Grid Faults

In contrast to AC devices, faults in the DC grid or in other devices play a special role and can place a particular load on connected devices [10]. If a short circuit occurs in the grid or in a nearby device, the DC links of the connected devices are immediately discharged. This results in very high currents, which can be up to a thousand times higher than the operating current in real devices [12].

During such a discharge of the DC link capacitance (see Fig. 5), not only the capacitor is stressed. All conductive tracks and possibly existing connectors are also overloaded, whereby these develop contact

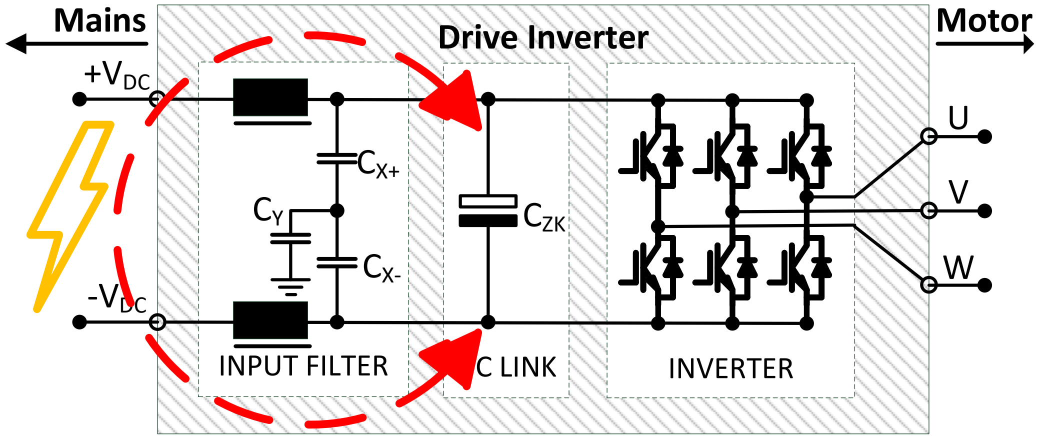

Fig. 5: Drive Inverter with the main components and an external short-circuit fault and resulting current flow

resistances or even break down completely. Measurements already carried out show however: Especially the inductance in the input filter (see Fig. 2), which usually has only a few turns, can get the entire voltage in the worst case: 0 V at the DC terminal and the full voltage in the DC link. The result may be voltage flashovers and thus local thermal overloads, as well as component failure.

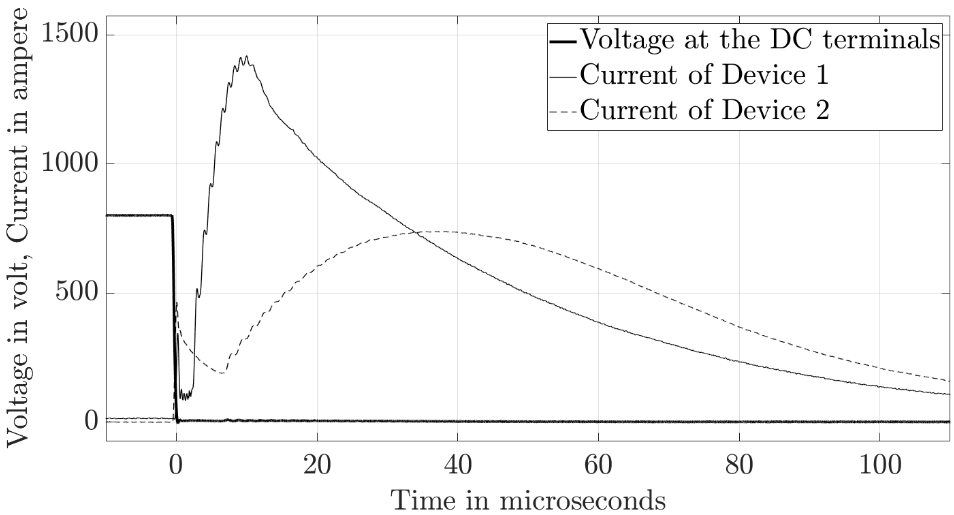

Fig. 6: Measured voltage and current curves of a discharge process of two drive inverters with different DC link capacitors: Film capacitor in Device 1 and electrolytic capacitor in Device 2

Fig. 6 shows the measurement of an external discharge of the DC links of two different devices of the same power class ($P_{nom} \approx 1\,kW$). Device 1 uses a film capacitor as the DC link capacitor and accordingly shows a rapidly increasing current curve. This is due to the low attenuation and the comparatively low impedance of the film capacitor. Device 2 has an electrolytic capacitor in the DC link. Due to parasitic effects, the current rise is limited and the amplitude is also smaller. The maximum current, on the other hand, is maintained longer. In both cases, the discharge current reaches a maximum of more than 1000 times the nominal operating current.

Conclusion

Devices in the industrial environment are subject to high demands on their lifetime: They must be achieved. For this to work, the electrical influences on the device must be known when selecting the components. The most important influencing factors here are: Static and dynamic voltages, ripple currents flowing between individual devices, and fault events in the DC grid that lead to sudden discharges. All these influencing factors can have a negative impact on the lifetime. Damage and premature aging can be avoided by the correct design and selection of components such as semiconductors, capacitors and also the inductances of the input filter.

The paper shows the permissible voltage ranges of DC INDUSTRIE in relation to time Devices can be easily designed for this with suitable input filters and DC link capacitors. Furthermore, the determination of ripple current loads is possible by a simple measurement and a test circuit, so that overloads can be detected already during initial operation. Devices must be designed for fault events such as short-circuits that can occur during operation and must not be impaired. Since these are short-term events, devices can also be designed for them without obstacles. Therefore, these listed influences do not stand in the way of a wide use of devices, such as drive inverters, in an open industrial DC grid.

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