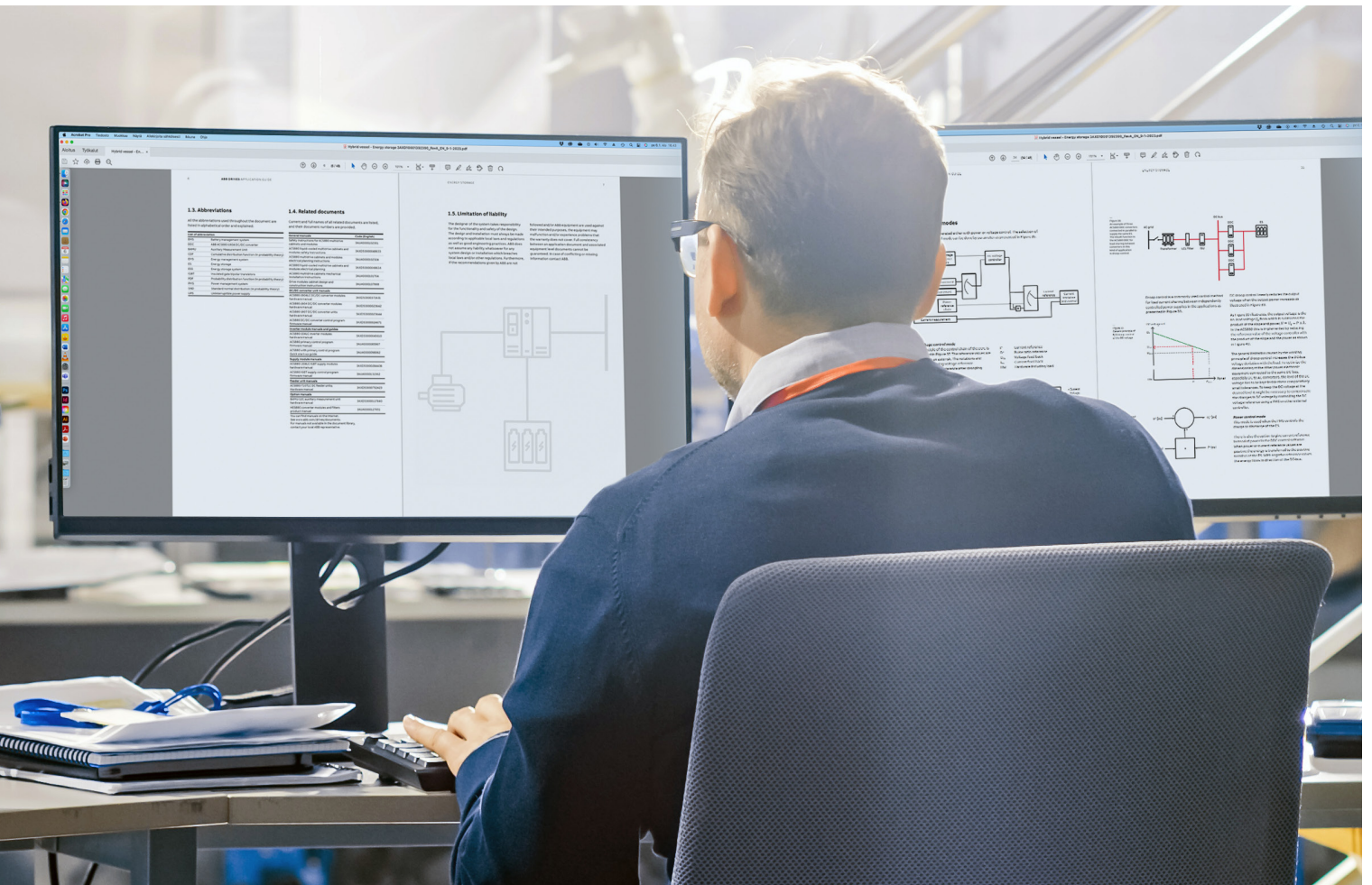


ABB DRIVES

Energy storage

Application guide



- The purpose of this document is to give sufficient information about the converter technology used in energy storage applications
- This guide is primarily intended for engineers in sales, sourcing and electrical system designing

This guide is focused on features, operation and dimensioning for the configuration and design of a converter system.

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1. Introduction

1.1. Purpose of the document

The purpose of this document is to give sufficient information about the converter technology used in energy storage applications. This guide is focused on features, operation and dimensioning for the configuration and design of a converter system. It is primarily intended for engineers in sales, sourcing and electrical system designing. Detailed information about parameters and connections is available in product manuals and order related drawings.

This application guide will give the reader information about energy storage systems available on the market and their specific features, as well as a presentation of the system solutions offered by ABB Drives to integrate an ESS solution on a ship.

This guide focuses on converters used with energy storage applications, offering and features. Even though energy storage units are not part of ABB Drives offering portfolio, their main capabilities and characteristics are presented in this guide as they affect the choice and dimensioning of converter modules. The energy storage unit does not belong to the converter unit delivery. The customer (or the system integrator) must equip the DC/DC converter with a suitable energy storage system.

For more details on energy storage units, please contact the manufacturers of those systems.

Even though a range of options and solutions is proposed, ABB Drives is not responsible for the selection of other components and control but ABB Drives offering.

1.2. Definitions

All the central terms are defined, and the terms are introduced in their appropriate context to provide the reader an understanding of the topic that is discussed.

- AC grid: AC electricity distribution system of a vessel.
- DC/DC converter: power electronics unit which is used to convert the current or voltage level of energy storage to suit the one of the DC-buses or vice versa.
- DC-bus: intermediate DC-circuit of ACS880 multidrive which connects together the converter modules.
- DC grid: external DC-circuit, which connects together the converter modules and other consumers or equipment.
- Energy storage: device that stores electrical energy, for example, a battery or a super capacitor.
- Multidrive: Electronic equipment used to regulate the power fed from the electrical supply to the motor. It controls several motors which are typically coupled to the same machinery and includes a supply unit, and one or several inverter units.

1.3. Abbreviations

All the abbreviations used throughout the document are listed in alphabetical order and explained.

List of abbreviation	
BMS	Battery management system
DDC	ABB ACS880-1604 DC/DC converter
BAMU	Auxiliary Measurement Unit
CDF	Cumulative distribution function (in probability theory)
EMS	Energy management system
ES	Energy storage
ESS	Energy storage system
IGBT	Insulated gate bipolar transistors
PDF	Probability distribution function (in probability theory)
PMS	Power management system
SND	Standard normal distribution (in probability theory)
UPS	Uninterruptible power supply

1.4. Related documents

Current and full names of all related documents are listed, and their document numbers are provided.

General manuals	Code (English)
Safety instructions for ACS880 multidrive cabinets and modules	3AUA0000102301
ACS880 liquid-cooled multidrive cabinets and modules safety instructions	3AXD50000048633
ACS880 multidrive cabinets and modules electrical planning instructions	3AUA0000102324
ACS880 liquid-cooled multidrive cabinets and modules electrical planning	3AXD50000048634
ACS880 multidrive cabinets mechanical installation instructions	3AUA0000101764
Drive modules cabinet design and construction instructions	3AUA0000107668
DC/DC converter unit manuals	
ACS880-1604LC DC/DC converter modules hardware manual	3AXD50000371631
ACS880-1604 DC/DC converter modules hardware manual	3AXD50000023642
ACS880-1607 DC/DC converter units hardware manual	3AXD50000023644
ACS880 DC/DC converter control program firmware manual	3AXD50000024671
Inverter module manuals and guides	
ACS880-104LC inverter modules hardware manual	3AXD50000045610
ACS880 primary control program firmware manual	3AUA0000085967
ACS880 with primary control program Quick start-up guide	3AUA0000098062
Supply module manuals	
ACS880-204LC IGBT supply modules hardware manual	3AXD50000284436
ACS880 IGBT supply control program firmware manual	3AUA0000131562
Feeder unit manuals	
ACS880-7107LC DC feeder units; Hardware manual	3AXD50000752423
Option manuals	
BAMU-12C auxiliary measurement unit hardware manual	3AXD50000117840
HES880 converter modules and filters product manual	3AUA0000127651

You can find manuals on the Internet. See www.abb.com/drives/documents. For manuals not available in the document library, contact your local ABB representative.

1.5. Limitation of liability

The designer of the system takes responsibility for the functionality and safety of the design. The design and installation must always be made according to applicable local laws and regulations as well as good engineering practices. ABB does not assume any liability whatsoever for any system design or installation which breaches local laws and/or other regulations. Furthermore, if the recommendations given by ABB are not

followed and/or ABB equipment are used against their intended purposes, the equipment may malfunction and/or experience problems that the warranty does not cover. Full consistency between an application document and associated equipment level documents cannot be guaranteed. In case of conflicting or missing information contact ABB.



2. Energy storage systems (ESS)

2.1. Contents of this chapter

This chapter presents a range of factors to be considered while designing an ESS in a marine vessel. The information concerning super capacitors, batteries and other third-party equipment laid out in this document are an overview meant to give a general understanding of the factors to be considered during the design of an ESS. The dimensioning and detailed design of the installation of third-party equipment must be done according to the instructions of its manufacturer. The considerations will guide you in the process of selecting the ideal solution and products for your needs.

2.2. Background and defining terms

The basic role of energy storage is the same across all applications: to absorb energy generated at one time and to discharge it to supply power at a later time. The choice of storage medium for each application is dependent on the required power rating and the duration for which it may need to continuously charge or discharge.

With energy storage there is no universal solution suited for every application.

Selecting the right storage medium for a particular application requires a thorough understanding of

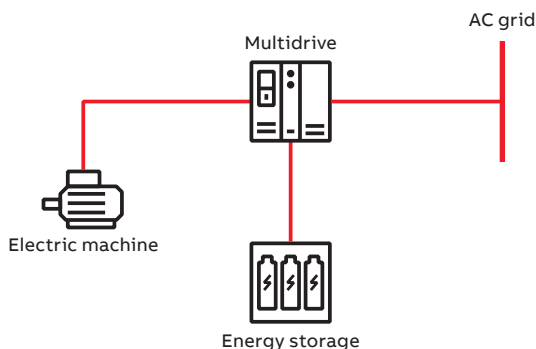
the functional demands on the storage system, as well as the ones this system places on the grid.

Most electrical energy storage technologies – including batteries and supercapacitors – are based on direct current (DC). To connect these storage media to alternating current (AC) grids, mainly used for power transmission and distribution, requires a conversion step using power electronics.

The same is true for energy storage technologies that are natively AC. They also rely on power electronics to be integrated optimally into an AC grid.

Once electrically connected to the grid, an ESS requires effective control. Solid-state power electronics can respond almost instantly to commands. Exploiting this capability demands that controllers react with the same speed. System designers must take into consideration the infrastructure in place, the logic and algorithms to determine the right command to be implemented. Figure 1 is a simplified representation of an ESS.

Figure 1:
Energy storage
connected
to ship grid via
multidrive



2.3. Functions and benefits

ESSs store electrical energy at times of surplus and release it at times of deficit; helping to drive energy efficiency.

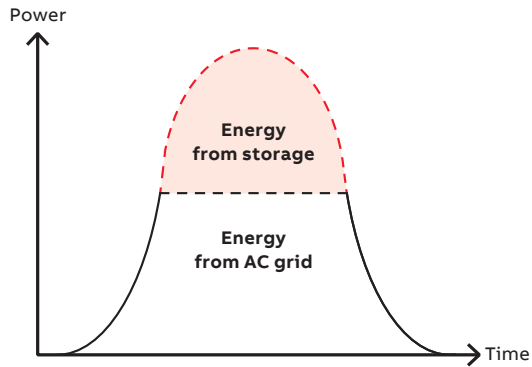
Introducing an ESS between the generators and the consumers allows the grid to balance electrical demand with the supply from the generators. The use of an ESS leads to better efficiency in the use of energy sources.

An ESS can be used as an alternative to back-up generators such as diesel-based systems to improve the emissions performance of a ship. They provide a lower carbon approach to ensure the continuity of supply in the event of an external power interruption.

2.3.1. Peak shaving

The peak shaving function is used to reduce load variations caused by waves and adverse weather conditions. Figure 2 presents a power over time graph of the peak shaving function.

—
Figure 2:
Peak shaving



Its goal is to reduce the load peaks, allowing for a smaller dimensioning of the grid and reducing the number of starts and run hours of additional gensets. The ESS compensates for load variations in the network in such a way that the engines only see the average load of the system.

Peak shaving reduces fuel consumption and increases interval between maintenance times.

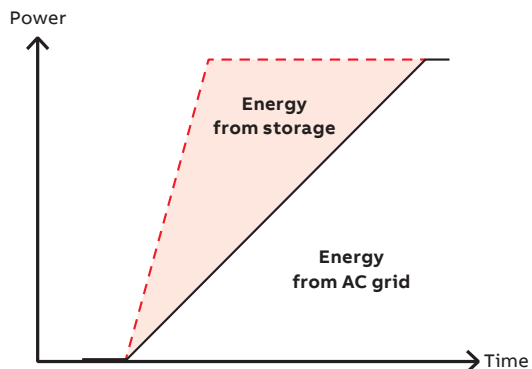
2.3.2. Enhanced dynamic performance

In marine conditions the power supply must adapt to load changes. An ESS can assist gensets without the need to increase the power capability of those generators.

The ESS supplies power to the AC grid for a time, as shown in Figure 3. This function, called enhanced dynamic performance reduces fuel consumption.

The ESS can be used as a short time back-up power, such as an uninterruptible power supply (UPS), to run propulsion. This can happen for example during grid lost situations. Therefore,

—
Figure 3:
Enhanced dynamic
performance



the functionality of back-up power increases safety onboard and can also lead to reduced fuel consumption and longer intervals between engine maintenance operations.

The ESS can also be used to improve the dynamic behavior of the gensets, especially the ones associated to gas-only engines, which are known to have a low load response. The load response challenge of the present gas-only engines is caused by the accuracy requirements of the AFR (air fuel ratio). The AFR is calculated by dividing the mass of air with the mass of fuel. Following a rapid increase of the load the AFR drops due to the inertia of the turbo charger. This increases the chance of knocking. Additionally, a gas-only engine's over-boosting (of air) capabilities are limited due to the risk of misfiring when mixtures are too lean. To avoid these side effects engine manufacturers limit the load response rate.

2.3.3. Zero emissions operation

The ESS powers the system in such a way that the engines can be turned off. ES offers a solution to cut down operational costs and reduce environmental

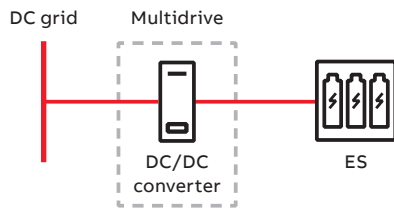
emissions by enabling emission-free operation for example in harbor areas. Another benefit is a quiet engine room during maintenance.

2.4. Integrating Electrical ES to the System

The ESS may be integrated to the power system in various configurations depending on the application. The following section describes integration to a DC grid, and to an AC distribution system.

2.4.1. ESS with a DC/DC converter (DDC)

—
Figure 4:
ES integrated
to a DC grid



As shown in Figure 4, the battery is connected to a DC-bus in the power system through a DDC. Compared to the AC integration of batteries, DC provides a more compact solution and faster control, when the energy consumer is connected to the same DC-circuit (for example a motor drive).

2.4.2. Direct Online (DOL)

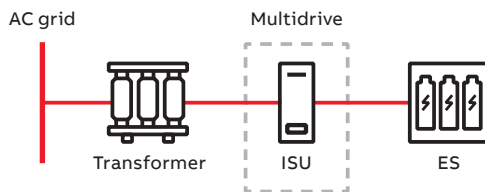
In this mode the battery is connected directly to a DC-bus in the power system. Since the battery is connected directly, it will define the voltage of the DC-bus. Consequently, all other equipment must be selected according to the voltage span of the battery (up to 25% variation).

The main advantages of a DOL solution are energy efficiency and a smaller footprint as there is less hardware required. However, the disadvantage is less control over the power flow.

2.4.3. ESS Integrated to an AC System

For an AC power system, the battery must be connected through a DC/AC converter and a transformer. This can be used in both low voltage and high voltage applications.

—
Figure 5:
ES integrated to
an AC system



The converter and transformer must be dimensioned for the lowest battery voltage, and at the same time the converter must be able to handle the maximum battery voltage. This typically leads to a large de-rating of the converter, and therefore relatively large converters.

Figure 5 represents an ES connected to the AC grid of a ship via a multidrive.

2.5. ESS solutions

In marine vessels, power electronics have a major impact on fuel saving, particularly through the integration of ESS and the electrification of propulsion systems through variable speed drives (VSD).

Energy storage devices currently being used in several applications consist of batteries and supercapacitors.

ESS technologies vary from each other in terms of expense and technical aspects such as power density, energy density, charge and discharge time, operating temperature, lifetime, environmental impact, and maintenance requirements as in energy applications the storage unit is continuously discharged or charged over a period of time sometimes taking several hours.

2.5.1. Control systems

Power Management System (PMS)

A PMS is a complete switchboard and generator control system that controls power generation and distribution.

The PMS on board vessels is responsible for functions such as load sharing among different power sources and load shedding when generated power is insufficient.

The PMS monitors and estimates power consumption and active operation using real time information received and manages the ESS according to the host controller demands.

Battery Management System (BMS)

The BMS is a set of electronics that monitors the battery’s performance to keep it from operating outside of its safety margins. The primary function of the BMS is to protect the battery cells from damage caused by being overcharged or over-discharged.

It typically monitors the cell voltage, temperature and current. Based on the monitored information,

it calculates the state of charge (SOC) and the current limits. If the limits are exceeded, it will trip the battery.

The BMS also balances the charge across the cells to keep each one functioning at maximum capacity. This is critical to the battery’s safe operation, overall performance, and longevity.

Converter level control

ACS 880 converters are equipped with an inbuilt control system to make it easier for the user to achieve the desired voltage or power output according to the reference. Converter level control is not designed for system control and so does not include the functions for this purpose. A PMS and BMS are required for system control of the ES in the ship.

The control of the DC/DC converter is discussed more thoroughly later in sections 3.5 “Control modes” and 3.6 “System control”.

2.5.2. Batteries

Batteries are devices that transform chemical energy directly into electrical energy through an electrochemical oxidation-reduction reaction. They have a high total energy storage capacity, but the rate at which the energy can flow out of batteries is low compared to supercapacitors. However, stress and high levels of heat generation can cause damage and limit the batteries’ cycle-life – a measure of how many times a

battery can be charged and discharged before losing performance.

Batteries are usually used in a stack of connected individual cells to gain the desired voltage and capacity as shown in Figure 6. This sets requirements for the system operating the stack because the cells need to be in balance with each other to avoid malfunctioning.

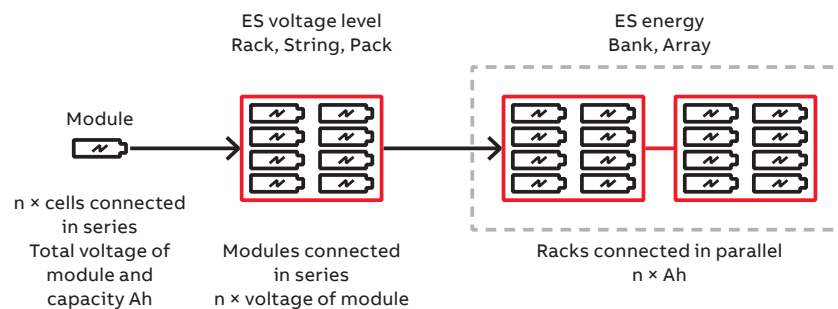


Figure 6: Batteries based ES configuration

Electric model of a Li-ion battery

The most commonly used batteries are one of the several Li-ion battery types. Li-ion batteries are typically modelled in the literature by a voltage source and serial resistance, which describes the galvanic circuits in the battery. In the more accurate models, it includes serial connected one or several parallel connected resistance-capacitance pairs as illustrated

in Figure 7. The component values of the R/C pairs are a function of several parameters such as temperature, state of charge etc. and the number of these elements depends on the desired dynamic accuracy. For the simplicity of the calculations and availability of the parameters the models with two or less R/C pairs are typically used.

Figure 7: An equivalent circuit of the Li-ion battery

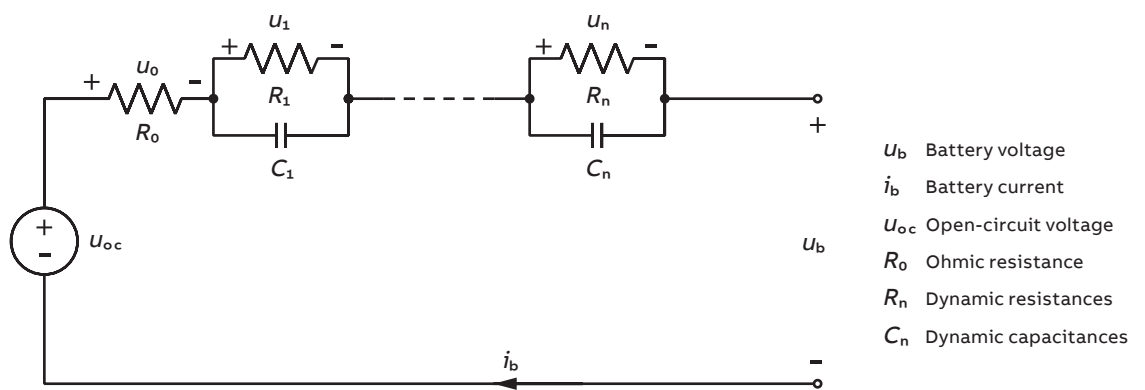
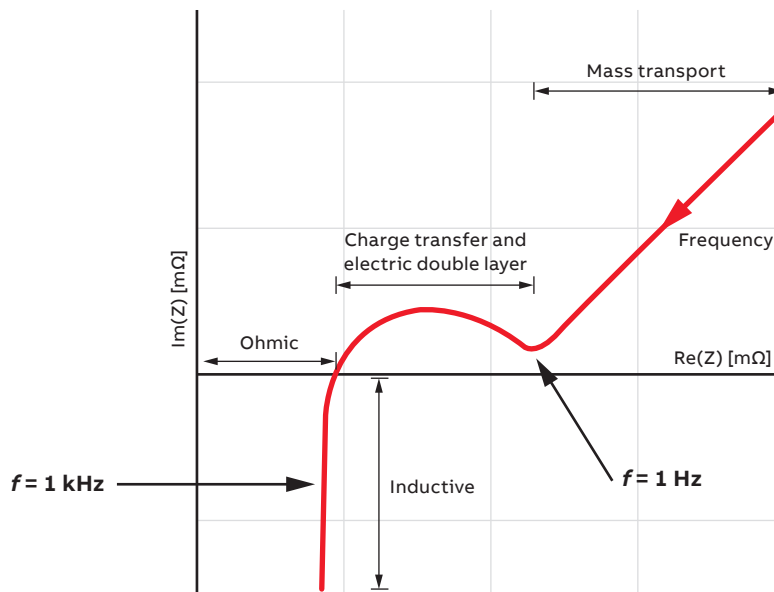


Figure 8 gives an idea of the dependence of the complex impedance and the frequency of a Li-ion battery. Note, that the tracer in the figure depends on the state of the battery.

The short-circuit current peak is limited only by the ohmic resistance (and the leakage inductances) of the circuit, thus it can be very high, unlike in traditional lead acid batteries.

Figure 8: Impedance of a Li-ion battery



Battery energy

Figure 9 presents the charging and discharging cycle of a battery. At time instant t_1 the battery is fully charged, and voltage is U_1 . When the battery is starting to discharge and until time instant t_2 the voltage decreases to the value U_2 . Batteries have an exponential discharge curve which provides steady power almost to the end of its energy capacity, the voltage drop being above 10%.

After discharging, the battery will be charged from time instant t_2 until t_1 . The voltage returns

from value U_2 back to U_1 . Charged and discharged energies are equal.

Charging time depends on the battery and ranges from tens of minutes to several hours. The process is internally protected with electronic circuits in each cell.

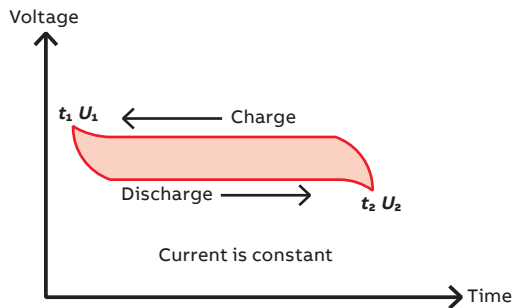
The following formula lets you calculate the available energy (E) over the charging cycle t_1-t_2 as a function of load power $P(t)$ or average power (P_{av}):

$$E = \int_{t_0}^{t_1} P dt = P_{av}(t_1 - t_0)$$

By dividing the energy with the voltage, you can further derive from the above equation a new one giving the consumed charge of the battery

$$Q = \frac{E}{U} = \int_{t_0}^{t_1} i dt = I_{av}(t_1 - t_0)$$

—
Figure 9:
Battery charging and
discharging curve



C-rate

The maximum current of the battery is defined by its capacity and C-rate. The C-rate is a measure of the rate at which a battery is charged or discharged (I_{max}) in relation to its maximum capacity (Q).

$$C = \frac{Q[Ah]}{I_{max}[A] * 1[h]}$$

A C-rate of 1C corresponds to a one-hour discharge, a 0.5C rate is a two-hour discharge

$$(C/2 = \frac{Q}{I_{max}*2h}) \text{ and so on.}$$

Impact of the charge/discharge rate on battery charge

The battery charge/discharge current has an impact on the available charge in the battery. This impact is described mathematically by Peukert's law, which explains how the rate of discharge influences the battery's actual capacity. When the battery is run at a high rate of discharge, the internal resistance within the battery creates a voltage sag that ultimately shortens how long it will last.

Peukert's law can be written as:

$$t = \frac{Q_P}{I^k}$$

where:

- Q_P is the capacity when discharged at a rate of 1 amp.
- I is the current drawn from battery (A).
- t is the amount of time (in hours) that a battery can sustain.
- k is a Peukert's constant. Typical values for Peukert's constants of lead batteries are around 1.3 and respectively for lithium batteries around 1.05.

Note on battery dimensioning

The information contained in the above subsections is meant as an aid to obtain a rough estimate of the battery system requirements. In addition to the above a number of factors need to be taken into consideration to ensure that the

battery fulfills all requirements (e.g., losses, lifetime requirement, temperature, etc.). Due to its complexity the dimensioning of the battery must be done according to the manufacturer’s instructions.

Lithium-ion batteries

Lithium-based technology is increasingly being used for energy storage in vessels due to its good power density and high cell voltage, and this despite its more complex charging process.

report information about the state of battery to the power management system (PMS).

Note: BMS and PMS functions are described in the section 2.5 about system control.

Their charging and discharging cycles are internally protected with electronics circuits in each cell and the battery management system (BMS). The function of the BMS is to protect and

There are several types of Lithium-ion batteries, with varying properties. Commonly they have a low DC-resistance, which leads to high peak-value.

2.5.3. Supercapacitors

Supercapacitors store energy in terms of an electric field and are known for their high symmetrical charge and discharge rates. They can be discharged and charged up to millions of times and have a much faster charge-storing processes than batteries (around 1µs-1ms cycle). Supercapacitors have low equivalent series resistances that enable them to supply power efficiently and are generally used in high power applications where high power is required for a short time. In addition to good cycling capabilities, supercapacitors have long shelf lives.

Figure 10 illustrates the individual structure of a supercapacitor. The key characteristics of supercapacitors are higher power density, faster charging and discharging due to lower internal resistance, enhanced life cycle, low voltage, and higher cost per Watt-hour (up to 20 times compared to Li-ion batteries).

One of the main drawbacks of these ESS is a relatively low energy density, linear discharge voltage, high self-discharge, and low cell voltage.

Supercapacitors are easier to cool than batteries due to their reduced internal resistance.

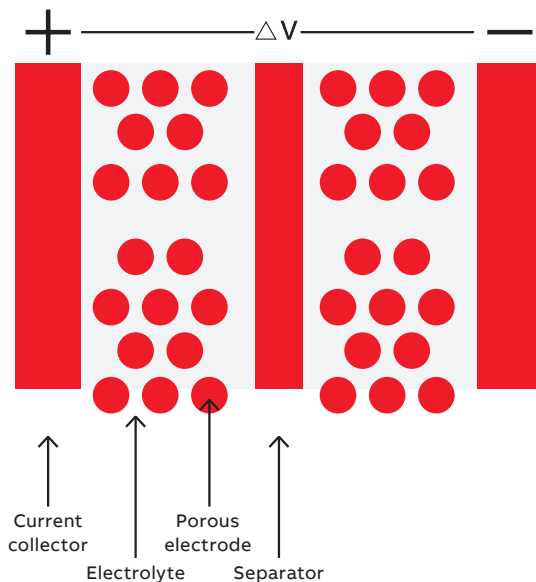
They have a wider thermal operation range than batteries and are better at discharging their stored energy quickly.

However, the voltage of a supercapacitor decreases on a linear scale, limiting the range of usable power. They also have a higher self-discharge rate than batteries.

The voltage of a capacitor can be expressed as charge over capacitance:

$$U = \frac{Q}{C}$$

Figure 10: Structure of a supercapacitor



The charge is a time integral of the product of the current $Q = \int_0^t i(t)dt$, yielding the voltage equation for the current and averaged current:

$$U = \frac{1}{C} \int_0^t i(t)dt = \frac{I_{av}}{C} t$$

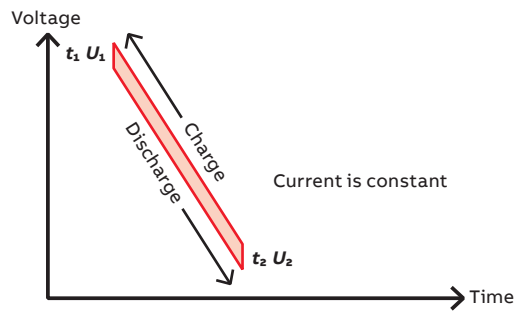
The voltage equation leads to a linear voltage-discharge curve with constant current as presented in Figure 11. At time instant t_1 discharge of the fully charged supercapacitor starts with voltage U_1 and continues until the voltage has dropped to value U_2 at the time instant t_2 .

The utilizable energy depends on the voltage at the start of the discharge and the allowed minimum voltage of the capacitor.

$$E_{out} = \frac{1}{2} C U_1^2 - \frac{1}{2} C U_2^2 = \frac{1}{2} C (U_1^2 - U_2^2)$$

Supercapacitors are typically stacked in integrated modules. An integrated module includes a management system for cell balancing, temperature measurement, voltage monitoring, and communication with the PMS.

—
Figure 11:
Supercapacitor
discharge and
charge curve

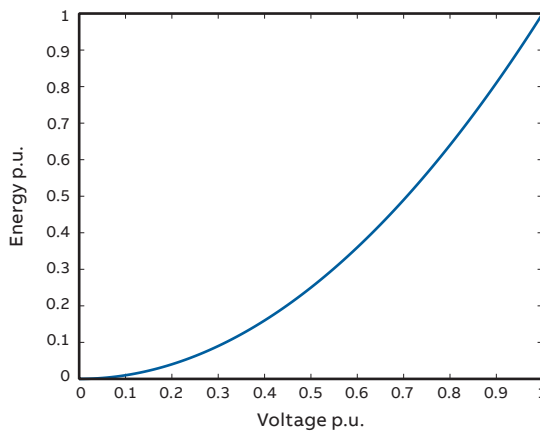


The energy contained by a charged supercapacitor depends on the capacitance and square of the voltage:

$$E = \frac{1}{2} C U^2$$

The trajectory of the energy as a function of voltage is presented in Figure 12.

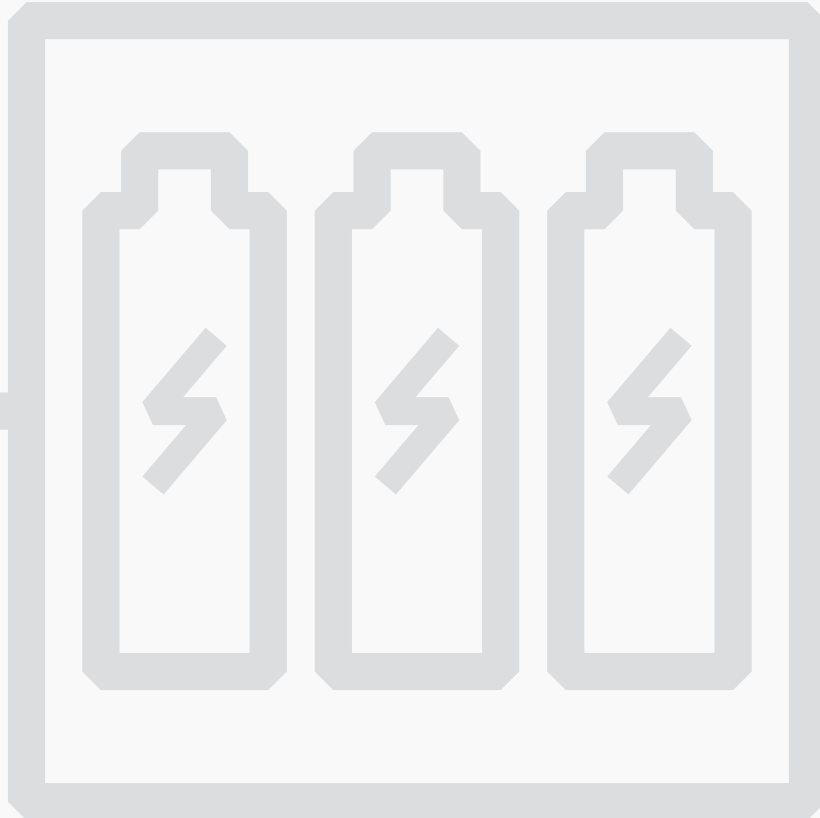
—
Figure 12:
Energy stored in
a supercapacitor
as a function
of voltage



3. System design

3.1. Contents of this chapter

This chapter is intended to give sufficient information for a successful design of the application. The basic phenomena related to the topology, control and protection of the ESS are presented.



3.2. Batteries and super capacitors

3.2.1. Direct online connection (DOL)

Both batteries and supercapacitors can be (with some limitations) connected directly to the DC-bus. The main reasons for using direct online connections are that they have better efficiency, and that they often (but not always) lead to a smaller footprint and lower capital expenses than connections through a DC/DC chopper.

The challenges of a DOL-connection are related to the control and protection of the ES (modern energy storages have extremely low internal resistance, leading to high short-circuit currents).

Connection of energy storage and disconnectors

DOL connection of an ES to the DC-busbar can be done via a connection cabinet (ACS880-7107LC). The connection cabinet includes terminals for cable connections, and fuses for short-circuit and overload protection of the cables.

The converters' DC-bus is equipped with discharging resistors. To prevent continuous discharging when the converters are idle, as well as to enable maintenance, it is recommended to equip the DOL connection with a disconnector. In order to mitigate the inrush current during connection, the DC-bus and ES must be charged to the same voltage before the closing of the disconnector. This is typically done by adjusting the level of the DC-bus voltage, as it is simpler and needs much less energy than the adjustment of the ES voltage.

Short-circuit protection

The short-circuit current must be checked against the short-circuit withstandability of the DC-bus. In a DOL connection current limiting fuses are usually needed to reduce the peak value of the short-circuit current. The short-circuit current (peak value and energy) sets the fundamental limit for the maximum capacity of the DOL-connected energy storage.

The designing of the ESS protection must address the following requirements:

- Limit the short-circuit current peak value.
- Ability to break the maximum short-circuit current in required time.
- Ability to operate in calculated time with the lowest desired DC voltage.
- Ability to operate in calculated time with the highest desired DC voltage.

The fuses in the drive connection cabinet must be able to disconnect the DC-bus from the faulty cable or energy storage. The protective device in the energy storage installation needs to break the fault current supplied by the ES.

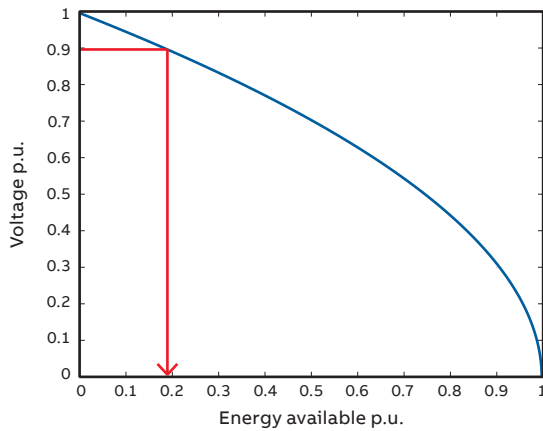
Overload protection

The BMS supervises the overload of the ES. To handle the overload the system must be designed to limit the power taken from the DC in case of the overcurrent and finally disconnecting the load from the ES if the limitation of the load fails. This is challenging especially with the batteries because their short-circuit currents varies a lot depending on their state of charge (SOC), age and their temperature.

Behavior of the voltage of the energy source

The voltage of batteries drops only slightly when discharged. On the other hand, the stored energy in capacitors is strongly bound to voltage. In a drive system the DC voltage level has a significant impact on the performance and dimensioning of all the converters which it supplies. This dependence usually leads to a small window of operation for the DC voltage level, limiting the amount of available energy for the capacitor bank. Figure 13 illustrates the impact of the operation window of the DC voltage on the available energy. This feature limits the use of DOL connection with capacitor energy storages.

Figure 13: Available energy of capacitor as a function of voltage. This example shows that only 20% of the capacitor's energy can be used if the voltage drop is limited to 10%.

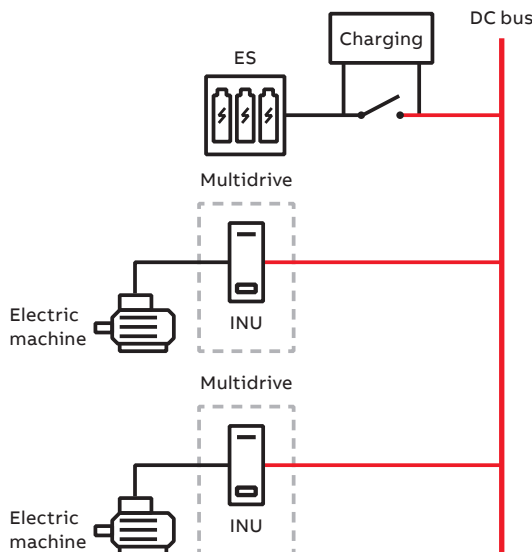


Even though the voltage of batteries drops only slightly when discharged, it must be taken in consideration when it is used in larger multi drive systems. In the worst case the lowered DC-voltage leads to a larger footprint and bigger capital expenses due to the higher current demand caused by the lower voltage.

Load current and efficiency

DOL connections do not have any switching losses, unlike power electronic connections. In addition, the current losses in a DOL connection are significantly lower than in semiconductors. For these reasons ESs with a DOL connection typically have better efficiency compared to their power electronic connected counterparts (the efficiency of the ACS880 DC/DC-converter is approximately 98.6%).

Figure 14: Energy storage connected directly to DC-busbar of ACS880 multidrive



However, a larger operation area of DC-voltage and thus also lower minimum voltage leads to lower AC voltage and higher AC current than in a supply unit with a fixed DC voltage level. The increased AC current causes increased losses in supply units (and possibly inverter units). In the worst cases this may lead to the need for larger units and thus an increased footprint and investment costs.

Capacitors have low internal resistance, which enables their use in applications requiring the ability to supply high but short current peaks. The low internal resistance of capacitors, coupled with high levels of stored energy, causes a high short-circuit current. The short-circuit current withstandability of the drive must be checked during the system design phase.

When the withstandability is exceeded the short-circuit current must be limited by using peak current limiting protection (e.g., fuses or circuit breaker).

Batteries, in addition to low internal resistance, also have a relatively low allowed maximum current. Exceeding this value, even for a relatively short time, may cause damage to the battery cells. A system with a DOL connected battery must be dimensioned to withstand the highest possible currents in the circuit.

Control of a DOL-connected energy system

The control of a DOL-connected ES can be split in two main parts, which are control of the connection switch and charge control.

Control of the ES-switch

Both the ES and the drive are typically equipped with a switch to enable their disconnection from the system. In order to prevent the inrush-current it must be ensured that the voltages on the DC-bus of the drive and on the ES are equalized at connection of the ES. This is done by voltage control and interlocking one of these switches. In this document the interlocked switch is called ES-switch.

Equalizing the voltages can be done by charging either the ES or the drives dc-bus.

Batteries keep their output voltage in the operational area of the frequency converter drive independently from the state of charge. This enables the equalizing of voltages by tuning the DC-bus voltage, requiring significantly less energy than changing the voltage of the ES. This is not possible with supercapacitors, which is one of the reasons why they are not used in DOL systems, the other reason being their inefficient utilization of the voltage area and charged energy.

Charge control and current control

An ISU is well adapted for use with a DOL connected ES. In these applications the BMS/PMS will give the desired DC-voltage reference or power reference to the ISU to charge the ES.

ES over-current can occur in situations when the ISU is charging the battery and supplying motor load simultaneously. If the motor load is disconnected by a failure in an uncontrolled way, then the only path for the ISU current is through the ES, possibly causing an overcurrent. This will be prevented by properly designing the system control.

Charge control of a DOL connected ES supporting the AC grid is challenging. The OGC is equipped with AC-voltage droop control and the ES charge must be controlled by the BMS and PMS by changing the offset value of the droop controller.

The OGC does not have inbuilt power limitation functions, thus rapid changes in the power balance of the AC grid can cause an over current in the AC connected energy storage systems. The time required to decrease the current to an acceptable level by changing the offset values may take a few hundred milliseconds. If the settling time is too long then the load must be disconnected, for example by stopping the converter. It is highly recommended to reduce the load, by limiting propulsion power in the case of electric propulsion or disconnecting the less important loads. This can be done by using the load information from the drive output or an external power relay.

3.2.2. Connection with a DC/DC converter (DDC)

DC/DC converters are used with supercapacitors and batteries in a similar manner. Supercapacitors can be discharged and charged usually between a few seconds and a few minutes, but they have a smaller capacity than batteries, and thus the biggest difference with batteries is the use of supercapacitors mainly as a short time energy storage.

Supercapacitors are used in applications such as harvesting braking energy from regenerating motors into the ES in systems or limiting the maximum power peaks in the supplying grid.

In peak shaving they are used to minimize the maximum load and thus also the size of gensets. They are also used in some UPS applications by leveraging the ES's capacity to keep processes running during power breaks in DC or AC grids.

Behavior of the voltage of the energy source

With DDCs the capacitance charge can be utilized even with voltages under the minimum DC-bus voltage level, allowing for a superior utilization of the capacitor capacity. DDCs also enable a more efficient dimensioning of drive systems as the DC-bus voltage is not reduced by the ES, leading to a more functional dimensioning of the other converters connected to the same DC-bus. They also improve battery protection by enabling the limitation of the battery's current, in normally operation, where the battery voltage is under the voltage level of the DC-bus.

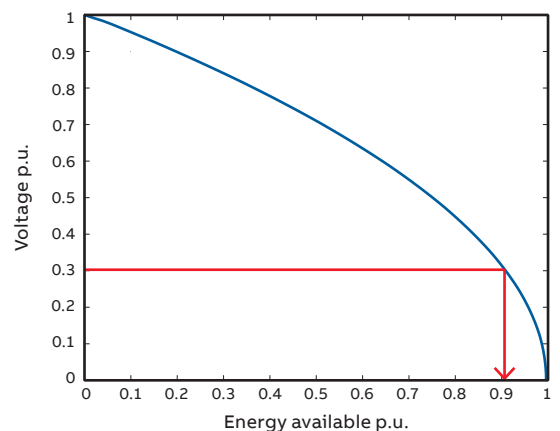


Figure 15:
Energy available as a function of capacitor voltage. Example shows that only 90% of the capacitor's energy can be used if the capacitor's voltage is utilized to 30%.

The voltage of batteries varies relatively little as a function of charge as illustrated in Figure 9. This makes a DOL-connection with batteries more attractive. However, there are several cases where it is justified to use a DC/DC converter to connect a battery to a DC-bus. This is the case especially with the larger multidrives, or when it is for other reasons important to keep the minimum DC-voltage level high.

Control of a DDC-connected energy system and an ES-switch

The main reasons to equip the energy storage with an ES-switch are:

- Safety during maintenance
- Avoiding the discharge of the ES through the feedback diodes when the DDC is not operated for an extended period of time. The feedback-diodes prevent the DC-bus voltage to be lower than the ES-voltage. This leads to the slow discharge of the ES when the main circuit breaker is open.

Before connection of the DDC to the ES the voltage of the DC-bus must be higher or as high as the voltage of the ES. To charge the capacitors in the DC-bus either the DDC integrated charging circuit (an option) or some other charging unit can be used. It is strongly recommended to equip the ES switch with interlocking, which ensures that a hazardous connection of the switch cannot take place.

The main principle in the control of the ES-switch is that the switch position is controlled by the PMS either directly or through the DDC. In idle state the DC-bus voltage is discharged through the discharging resistors in the DC-circuit.

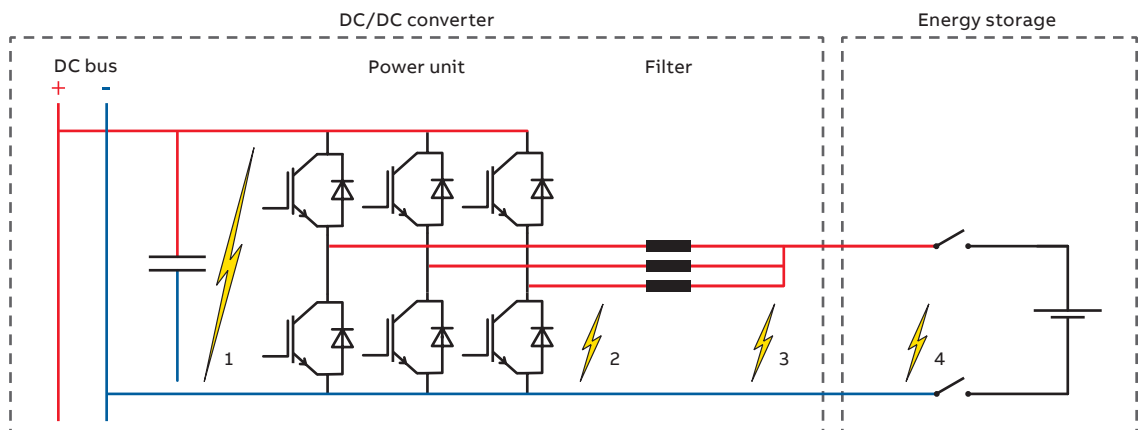
The control of the ES charge is managed by the BMS and PMS which give the reference to the DDC. Charging and control of the ES switch is further described in section 3.6 “System control”.

Short-circuit current and protection

In the DDC the chokes and semiconductors limit the DC-current peak value supplied by the ES to the DC-bus in case of a short-circuit in the drive. The power module of the DDC can effectively limit the short-circuit current from DC-bus when it takes place in the cable or in the ES. The cable must, however, be protected from the energy supplied by the ES. The short circuit must be switched off in the desired time, independent of the charge of the ES, and the maximum allowed short-circuit current of either the cable or the converter terminals cannot be exceeded.

The short-circuit current supplied by the DC-bus to the internal short-circuit are handled by the DC fuses in the DDC. The currents supplied by the ES to internal short-circuits and by the DDC to the external circuits need some attention from the system designer. Four different short-circuit cases, which must be analyzed in a standard connected DDC, are presented in Figure 16.

Figure 16: The short-circuit cases to be analyzed in the standard connection of the DDC



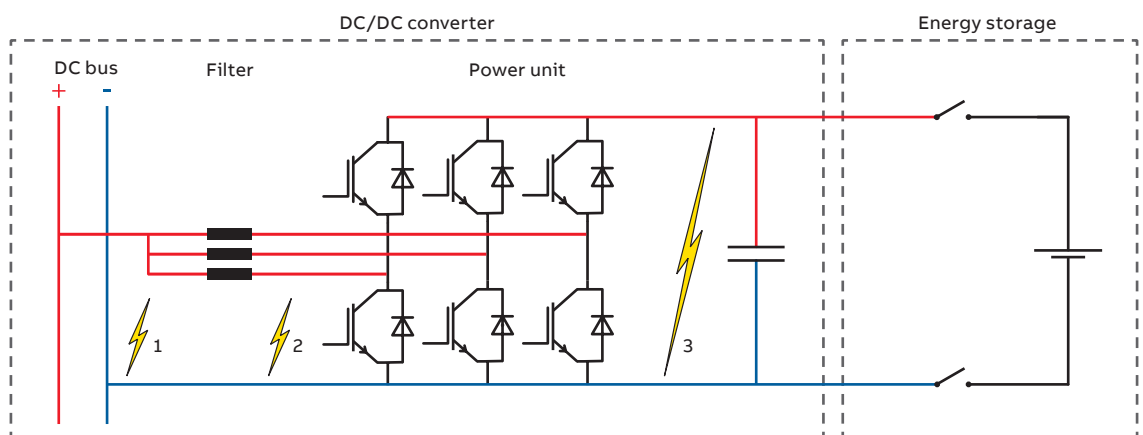
Cases one and two are actually identical from the ES point of view, because the impedance differs by the amount caused mainly by parallel current paths supplying case one. Cases three and four differ from each other by the impact of the cable impedance.

The protection must be completed with additional protection if the short-circuit current is too low to trip the fuses. This kind of protection can be

based for example on the monitoring of the voltage or current and time.

Figure 17 presents an approach for analyses of the points in the inversed connected DDC. In this connection the ES-voltage is higher than the DC-bus voltage. This typically ensures that short-circuit current is high enough to blow the fuses. Thus, the main concern is in the breaking capacity.

Figure 17:
Short-circuit cases
in the inversed
connected DDC



Short-circuit protection design must address the following issues:

- **Limitation of the short-circuit current.** The maximum value of the short-circuit current is not allowed to exceed the maximum peak value, the cabinet can withstand. The means to avoid the battery supplying a higher short-circuit current than the drive can withstand are splitting the battery into several separated supplied parts and using current limiting fuses at the ES-end of the cable.
- **Breaking capacity.** Short-circuit protection must be able to break the highest short-circuit current which can take place in the circuit to be protected. This may lead to the need to split the ES in several parts supplied by different cables with their own fuses.
- **Sufficiency of the short-circuit current.** For effective protection it is important for the short-circuit current to be high enough to disconnect the ES in the predefined time at the lowest operation voltage. In case the fuses are not tripped with low voltages additional protection must be used (e.g. overcurrent and/or undervoltage detection).

- **Thermal dimensioning and overcurrent protection.** The feeder unit must be selected to withstand the predefined load current. It also requires overload and short-circuit protection for the connection output cable(s).

The size of the fuses available for the DDC are given in the ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631) and ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).

Overload protection

Normally the DDC current limits can protect the cables and converter from overcurrent. However, attention must be paid to ensuring that the overcurrent cannot flow through the diodes. This can happen if the DC-bus voltage collapses under a high load (load is higher than supply) in the case of a standard connection (Figure 16). In an inversed connection, if the ES is discharged, the voltage tends to be lower than the DC-bus voltage commutating the current to the diodes (Figure 17). This also leads to lost current control.

Load current and efficiency

The converter is always subject to switching losses caused by switching on and off the semiconductors and resistive losses caused by the current in the semiconductive materials. The efficiency of the semiconductors is given in the ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631) and ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).

Despite the increased losses of DDCs compared to a DOL connection, the overall system is not adversely affected. A DDC enables a higher DC-voltage level and thus the current in all the other converters is reduced decreasing both, the switching losses, and the resistive losses in those. The total impact of the DDC on system level efficiency must be evaluated by calculating the total losses with and without the DDC.

3.3. DC/DC converter (DDC)

3.3.1. Purpose of a DDC

A DDC is a two-way power electronics unit set up between the ES and the DC-bus and is used with when the voltage of the ES (U_{ES}) is lower than that of the DC-bus. It enables keeping the DC-voltage level in the DC-bus at optimum level for the proper operation of the other units (e.g., INU, OGC, etc.) connected to the DC-bus as well as for economical design of the drive train.

proper operation of the power electronics despite the limitations of the physical properties of the semiconductors and control electronics. This sets the maximum and minimum limits for the output voltage. The values of the limits can be found in the ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631) and ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).

3.3.2. Standard Buck and Boost operations

Energy can be transferred in both directions through the ACS880 DDC. It uses two common operation principles called buck, and boost. The buck-operation is used when energy is transferred from a higher potential to a lower potential e.g., from DC-bus to an energy storage, while the boost-operation is used to supply the DC-bus from the storage.

Buck-operation

In buck operation the DC voltage is chopped by switching on and off the input voltage. The output voltage consists of pulses. The voltage is controlled by regulating the pulse width in relation to its length over a period of time. The ratio between the on-time and the full period (T) is called duty factor and it is noted D . In a buck-converter the output is filtered by a choke, which keeps the output current continuous in the designed operation area.

The interval between switching pulses cannot be infinitely short in the DDC. They are instead limited to a few microseconds in order to ensure

Figure 18: Buck-operation of a buck/boost converter. Current path when the upper IGBT is switched on (on the left side) and when it is switched off (on the right side).

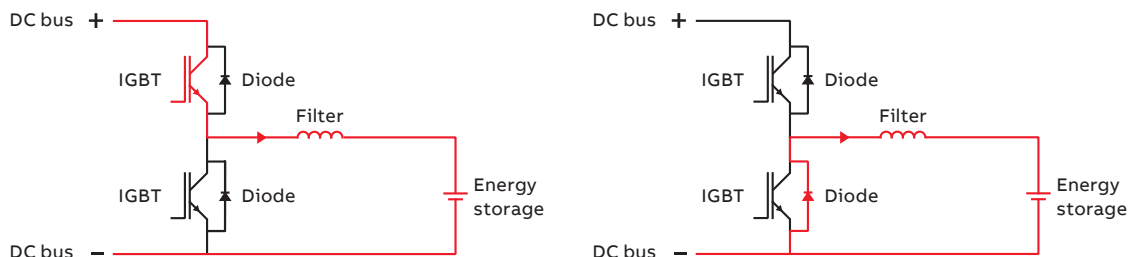


Figure 18 illustrates the principles of the buck operation of a converter. It shows how during duty time ($D \cdot T$) the IGBT in the upper branch is switched on, causing an increase of the current in the filter which increases the magnetic energy of the inductance. When the IGBT is switched off, the discharge of the magnetic energy of the inductance keeps the current flowing, supplying the load and the resistive losses of the circuit until the end of the switching period.

The consequence of this operation principle is that the output voltage (U_o) of the DDC is lower than the DC-bus voltage (U_{DC}). Neglecting the impact of losses, the input power (P_{DC}) and the output power (P_o) are equal. From this follows the equality:

$$U_o I_o = U_{DC} I_{DC}$$

And further the output current is

$$I_o = \frac{U_{DC}}{U_o} I_{DC}$$

As can be seen from the above equation, the ratio between input and output currents versus voltages are inverted. In other words, in a buck-converter the output current is higher than the input current.

The operation of buck and boost converters generally assumes that the load current is higher than current peak-to-peak value of the current ripple, $I \geq \Delta i$

The current ripple can be calculated as follows:

$$L \frac{di}{dt} = U_o = D U_{DC}$$

The current peak-to-peak value can be written:

$$i_{pp} = \frac{1}{L} \int_0^{DT} (U_{DC} - U_o) dt = \frac{1}{L} \int_0^{DT} (1 - D) U_{DC} dt = \frac{D(1 - D) U_{DC} T}{L}$$

The amplitude of the maximum current ripple and its respective duty time D can be found by solving the zero point of the derivative di/dD .

This yields the equations:

$$i_{pp_max} = \frac{U_{DC} T}{4L}$$

$$D(i_{pp_max}) = \frac{1}{2}$$

Figure 19 illustrates how the current ripple varies as a function of the output voltage in a buck-converter.

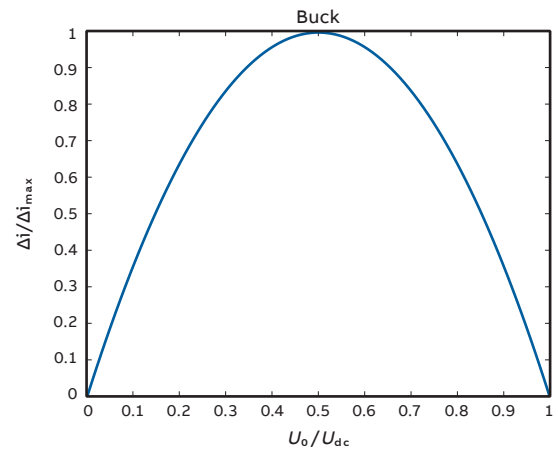


Figure 19:
Current ripple as a function of the output voltage

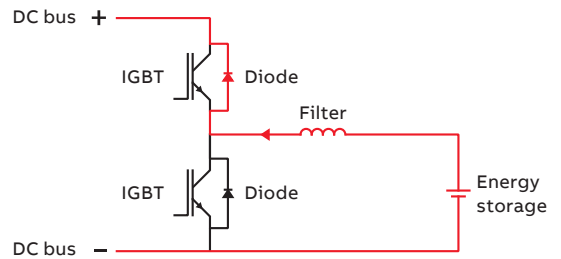
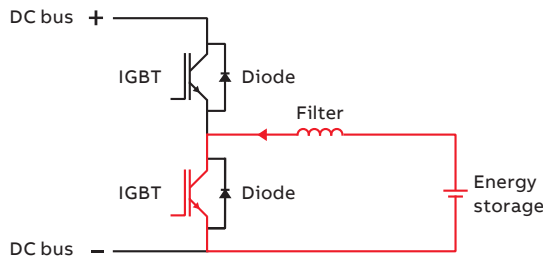
Boost-operation

The principle of the boost-operation is similar to that of a choke-filtered buck-converter. The difference being that the magnetic energy of the choke is now charged from the ES instead of the DC-bus and discharged to the higher potential DC-bus instead of the ES.

Figure 20 illustrates the principles of the boost operation of a converter. It shows how the

charging of the energy occurs by closing the circuit switching on the lower branch IGBT. When the duty time (DT) is passed the IGBT is switched off and the magnetic energy of the inductance is discharged to the higher potential DC-bus through the free-wheeling diode in the upper branch. After the full-time cycle T, the same two steps are repeated again.

Figure 20: Boost-operation of a buck/boost converter. The circuit on the left side illustrates the charging of the magnetic energy (the lower IGBT is switched on) and on the right side the discharging of it (the IGBTs are switched off).



You can calculate the current changes during duty time with this equation:

$$i_{pp} = \frac{1}{L} \int_0^{DT} U_o dt = \frac{U_o DT}{L}$$

and respectively the following equation gives the current changes during the discharging time:

$$-i_{pp} = \frac{1}{L} \int_{DT}^T (U_o - U_{DC}) dt = \frac{(U_o - U_{DC})(1 - D)T}{L}$$

In steady state operation, the current change over the full cycle must be zero.

$$\frac{U_o DT}{L} + \frac{(U_o - U_{DC})(1 - D)T}{L} = 0$$

From this can be derived the following equation for the output voltage:

$$U_{DC} = \frac{1}{1 - D} U_o$$

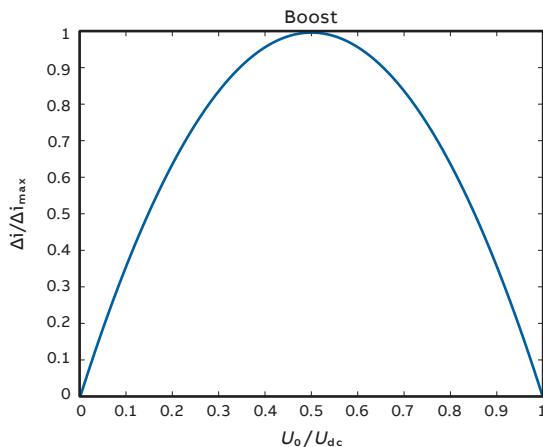
Furthermore, you can derive the amplitude of the maximum current ripple and its duty time in a similar way as before for buck-converters. The results are the same equations as the ones to calculate the current ripple for a buck-converter.

$$i_{pp_max} = \frac{U_{DC} T}{4L}$$

$$D(i_{pp_max}) = \frac{1}{2}$$

Figure 21 illustrates how the current ripple varies as a function of the output voltage in a boost-converter.

Figure 21: Current ripple as a function of the output voltage



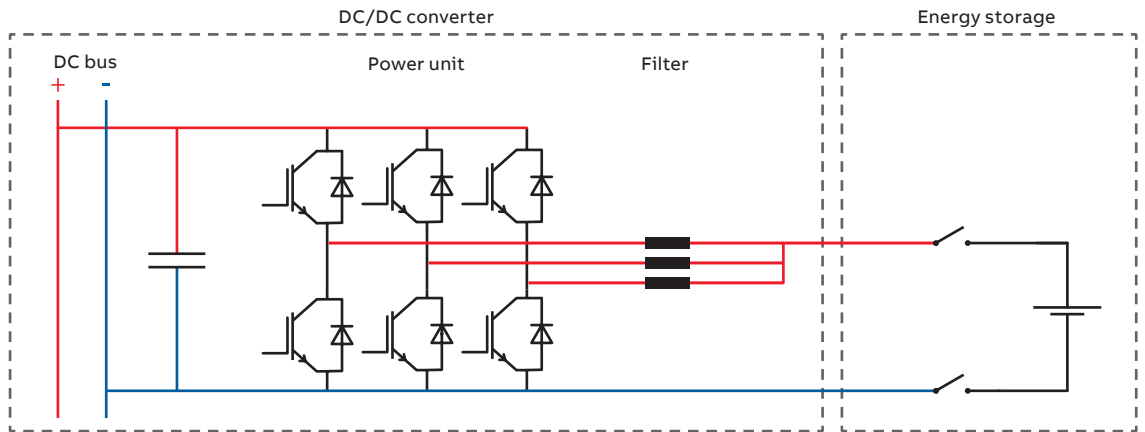
Interleaved three-pulse and six-pulse DC/DC converters

The power modules in the ACS880 DDC are the same three phase power modules used in ACS880 motor drives.

A three-pulse (aka three legged) DDC is presented in Figure 22. The ACS 880 DDC is operates at

4 kHz pulse frequency per leg. The converter module is run interleaved (the legs are operated with 1/3 period phase shift) resulting in a three folded (3 x 4 kHz = 12 kHz) output frequency called switching frequency. The term switching frequency in this document refers to the pulse frequency of the output voltage.

Figure 22: The interleaved three pulse DC/DC converter



A six-pulse converter consists of two three-pulse converters connected in parallel, each equipped with their own chokes, as shown in Figure 23. Both converter modules are controlled by the same control board, which takes care of the interleaving and increases the switching frequency to 24 kHz with a respective duty time of $T = 41.7 \mu s$.

The higher frequency further reduces the amplitude of the current ripple and thus also helps to filter it if needed.

The switching frequency of an interleaved DDC is inversely proportional to the number of its legs. Using the notation m for the number of legs, this can more formally be expressed as

$$f_{sw} = \frac{m}{T}$$

The direct consequence of the increased frequency is a better damping of the current ripples. Figure 24 shows the impact of the interleaving on the peak-to-peak value of the current for the example converter.

Figure 23: A six pulse DC/DC converter

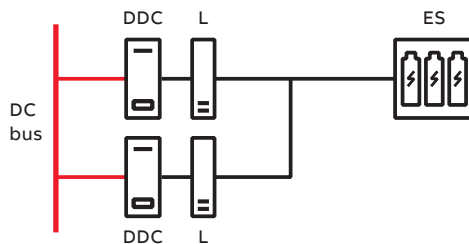
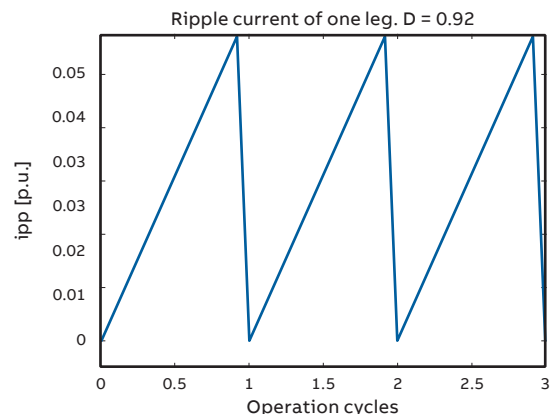
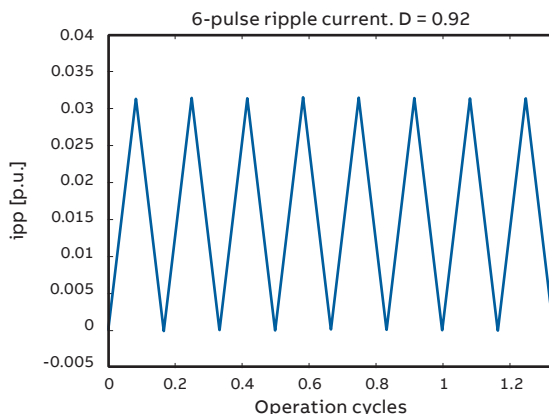


Figure 24: Six pulse converter current ripple at duty cycle value $D = 0.92$. The sum of the three leg currents on the left and the ripple of one leg on the right-hand side.



The maximum peak-to-peak value of the interleaved current is equal to the maximum peak-to-peak current of one leg divided by the total number of legs. Using the notation m for the number of the legs it can be written as

$$i_{pp_max} = \frac{U_{DC}T}{4mL} = \frac{U_{DC}}{4Lf_{sw}}$$

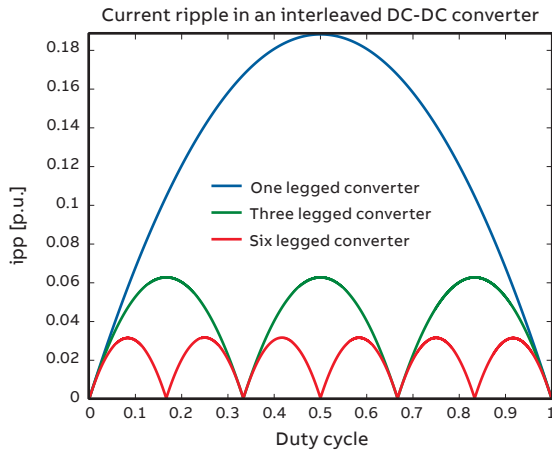
The trace $i_{pp} = f(D)$ has as many maximum points as there are interleaved legs in the converter. The duty factors giving the maximum value for peak-to-peak current are

$$D(i_{pp_max}) = \frac{(k - \frac{1}{2})}{m} \quad k = 1 \dots m$$

The current ripples of the different legs fully compensate each other with duty factors

$$D(i_{pp} = 0) = \frac{k}{m} \quad k = 0 \dots m$$

Figure 25: The relative peak-to-peak current ripple of the three different interleaving with the same inductance and switching frequency/leg



The relation between the duty factor D ($D = U_o/U_{DC}$) and the current ripple (in ratio to the rated current) of interleaved DDCs with different numbers of legs is shown in Figure 25. The ripple current values are calculated for an existing DDC converter and can vary slightly depending on the converter ratings. The peak to peak values at the duty factor, which gives the highest ripple current and at the rated dc-voltage are given in the ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631) and ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).

The current ripple is a function of the DC-bus and output voltages. The requirement for the current ripple is often given in the customer specifications as its peak-to-peak value. However, it can also be specified by giving

amplitude, effective value, or mean value of the current ripple.

Table 1 gives the conversion coefficients between peak-to-peak value and these other values.

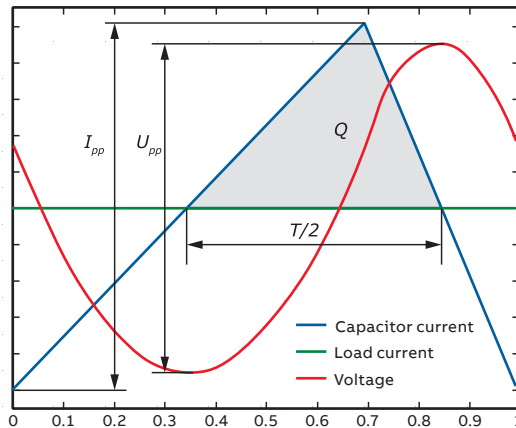
Table 1: Conversion coefficients

Peak-to-peak to amplitude	$\frac{1}{2} = 0.500$	Amplitude to peak-to-peak	2
Peak-to-peak to RMS	$\frac{1}{2\sqrt{3}} = 0.289$	RMS to peak-to-peak	$2\sqrt{3} = 3.46$
Peak-to-peak to mean	$\frac{1}{4} = 0.250$	Mean to peak-to-peak	4

Filtering the output voltage with a capacitor

When high requirements are set for the output voltage, an additional capacitor can be connected to the output to decrease the voltage ripple.

Figure 26:
The ripple current,
load current, charge
of the capacitor (ΔQ)
and capacitor voltage



The shape of the current ripple of a buck converter is a sawtooth wave, assuming that all the ripple current is fully flowing through the capacitor as shown in Figure 26. The charge of the capacitor is

$$\Delta Q = \int_0^t i_{pp} dt$$

When the capacitor current is higher than the load current the capacitor is charged and its voltage increases. The voltage is proportional to the charge and its maximum value is reached when the capacitor current decreases to the level of the load current after the charging period. The maximum change in the charge can be calculated from following equation and is illustrated in Figure 26

$$\Delta Q = \frac{1}{2} \cdot \frac{i_{pp}}{2} \cdot \frac{T}{2} = \frac{i_{pp} T}{8} = \frac{i_{pp}}{8 f_{sw}}$$

The respective voltage is:

$$u_{pp} = \frac{\Delta Q}{C} = \frac{i_{pp}}{8 C f_{sw}}$$

The worst case takes place with the highest peak-to-peak current, which is as earlier derived:

$$i_{pp_max} = \frac{U_{DC}}{4 L f_{sw}}$$

by substituting this to the equation for the voltage ripple we get the equation for the worstcase peak-to-peak voltage:

$$u_{pp_max} = \frac{1}{8 C f_{sw}} \frac{U_{DC}}{4 L f_{sw}} = \frac{U_{DC}}{32 L C f_{sw}^2}$$

The resonance frequency of the LC low-pass filter is roughly the same as its cut-off frequency. When the noise (in this case the voltage ripple) has a higher frequency than the cut-off frequency the damping of the low-pass LC filter is 40dB/decade (the LC filter is a second-degree filter).

The resonance frequency for the LC circuit is:

$$f_c = \frac{1}{2\pi\sqrt{LC}}$$

By substituting this expression in the equation above, the voltage ripple equation can be written:

$$u_{pp_max} = \frac{\pi^2}{8} \left(\frac{f_c}{f_{sw}} \right)^2 U_{DC}$$

Furthermore, the capacitance C can be solved from the following equation:

$$u_{pp} = \frac{i_{pp}}{8 C f_{sw}}$$

$$C = \frac{i_{pp}}{8 u_{pp} f_{sw}}$$

Capacitance is dimensioned according to the worst case. This usually means that it is dimensioned for i_{pp_max} :

$$C \geq \frac{i_{pp_max}}{8 u_{pp_max} f_{sw}} = \frac{U_{DC}}{32 u_{pp_max} L f_{sw}^2}$$

The equation above reveals an inversed quadratic dependence between the requested capacitance and the switching frequency. This means that the capacitance needed for a six-pulse converter is only 25% of the one needed for a three-pulse converter with an equal current ripple. However, the current ripple of a six-pulse converter is only half of the current ripple of the respective three-pulse converter. This further decreases the requested capacitor size to 12.5 % of what is needed for a three-pulse converter of the same size.

Load current ripple with a low pass filter

The output current ripple with a parallel connected filter capacitance can be calculated when the output impedance at the switching frequency is known. The current ripple (i_{pp}) in the DDC choke is not affected by the output filter and the ripple in the load current (i_{ppl}) can be given as a function of the current ripple. By assuming that the current

ripple is sinusoidal, then the equation for its maximum can be written as

$$i_{ppl_max} \approx \frac{1/i\omega C}{z_l(i\omega_{sw}) + 1/i\omega C} i_{pp_max}$$

Usually, the impedance is dominated by the resistance (R_l); following this we can use the earlier equation ($u_{pp} = \frac{i_{pp}}{8Cf_{sw}}$) and write the following equation for the maximum value of the load current ripple

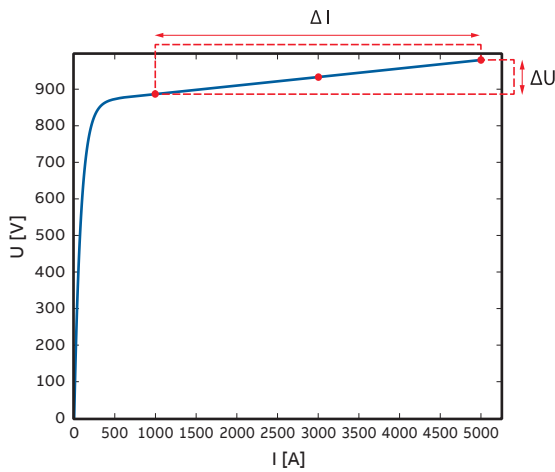
$$i_{ppl_max} \approx \frac{u_{pp_max}}{R_l} = \frac{i_{pp_max}}{8R_l C f_{sw}}$$

Further the required capacitance is

$$C \approx \frac{i_{pp_max}}{8R_l f_{sw} i_{ppl_max}}$$

Note, that for nonlinear loads the resistance R_l in the equations above is the slope of the U/I-curve in the operation area, $R_l = \frac{\Delta U}{\Delta I}$, as illustrated in Figure 27.

Figure 27: U/I-curve for a non-linear load



3.3.3. Parallel connection of DC/DC converter units

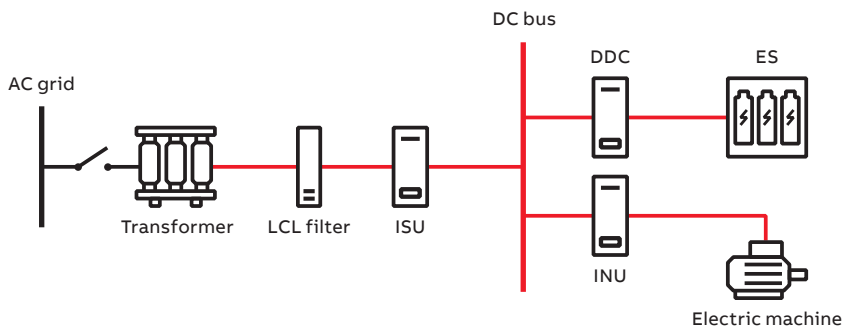
DC/DC converters connected parallel with other DC-voltage supplies

Figure 28 illustrates an example application, where a motor drive is supplied by a front-end converter (ISU) and an ES. There are restrictions to voltage control when several power sources are supplying the same DC-bus. The commonly used PI-controllers cannot be used to control the same voltage, as even a slight difference in the reference, the feedback or the dynamics of the controllers will cause their outputs to drift in the opposite direction.

There are a few possible ways to avoid this unstable cross-effect between the controllers:

1. The usual solution is to use droop control, which is also the only one, that can be realized without any external over running controller.
2. The alternative solution is to run the power supplies in power (or current) control modes. This method requires an external upper-level controller in voltage control mode giving the power (or current) references to the power supplies.

Figure 28: DC/DC converters connected in parallel with other power source in DC-bus

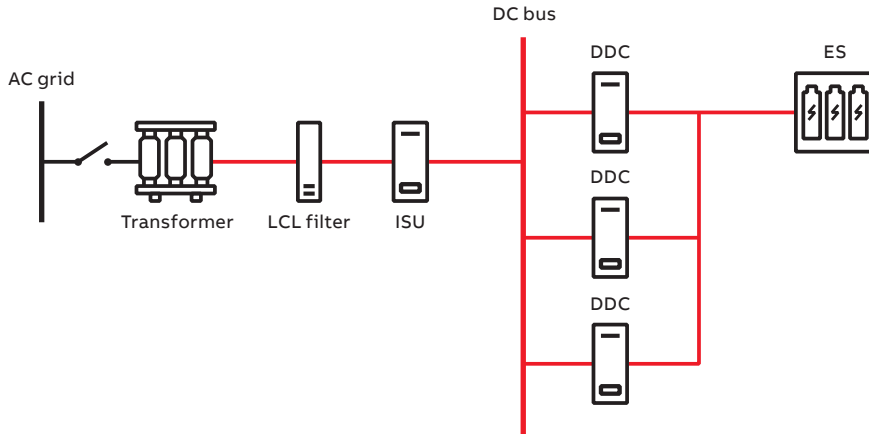


Several DC/DC converters supplying same load

The control board of an ACS880 DDC can control either one or two power modules depending on

the pulse number (three or six pulses). Several of these DDC can be connected to operate in parallel to the same DC-bus to supply the same load.

Figure 29: DC/DC converters connected in parallel to supply the high power



As the pulses of parallel connected converters are not synchronized, most of time the current pulses are in unsynchronized phase, leading to a partial cancellation of the current ripple.

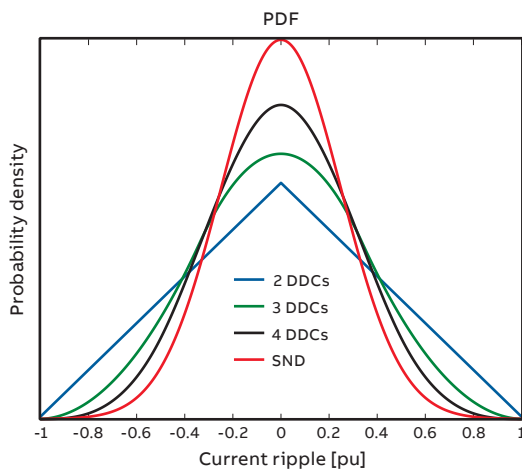
The current ripple is a triangle wave, meaning that all the values from the minimum to the maximum are as probable in any arbitrary instant of time. In other words, the shape of the probability density

function (PDF) is square. The sum of two PDFs is a convolution of the two of them. The PDF for the peak current in the parallel operation of independently modulated DDCs can be created by convolving the square PDF first with itself and then with the resulting sum functions

$$PDF_{2x} = PDF_x + PDF_x = PDF_x \otimes PDF_x$$

$$PDF_{3x} = PDF_{2x} \otimes PDF_x \dots$$

Figure 30: PDF of the ripple current of the independently controlled DC/DC converters



The notation \otimes stands here for the convolution integral. The PDFs are illustrated in Figure 30. It can be noticed that the PDF-function approaches the standard normal distribution (SND) when the number of parallel units increases.

A more demonstrative function is however the cumulative density function (CDF). The CDF can be calculated using the PDF by integrating it from - infinity to + infinity. Because a current peak can have only values between -1 and 1 the equation for the CDF can be written as

$$CDF(x) = \int_{-\infty}^{+\infty} PDF(x)dx = \int_{-1}^{+1} PDF(x)dx$$

Figure 31a presents the CDF functions of the ripple currents of parallel connected converters. The CDF is the probability for the current to be equal to or lower than a given value at an arbitrary instant of time. It can be understood as a representation of the amount of time during which the current is under that value. Figure 31b shows a magnification of the maximum peak current and its probability.

Figure 31: CDF of the ripple current of an independently controlled converter. Figure a present the full curvature and figure b is a magnification of the probability of the peak current.

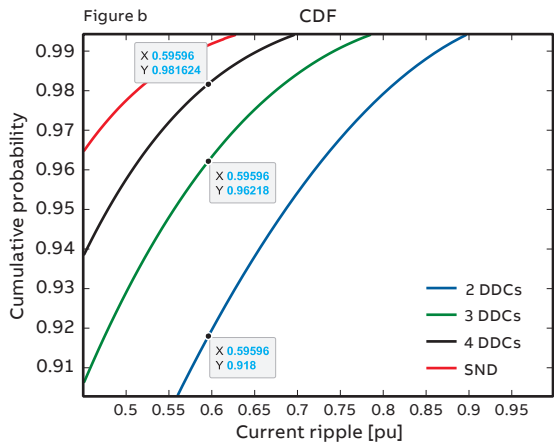
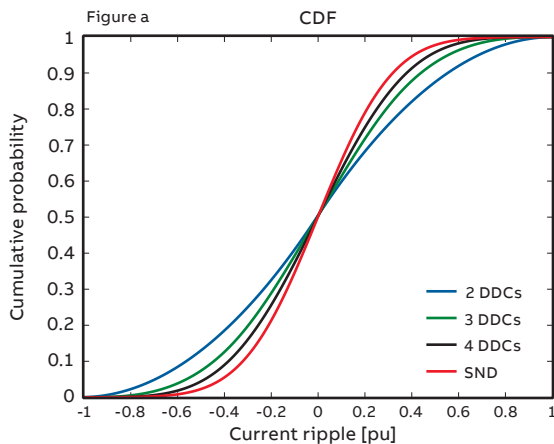
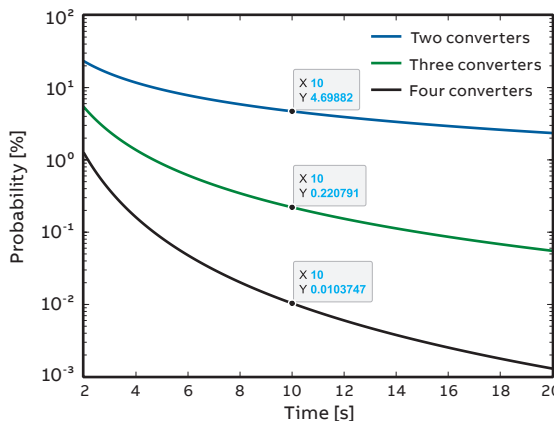


Figure 32: Probability of a synchronous state in function of the synchronous time



As seen in the figure, the number of converters has a strong impact on the probability of the maximum value. However, these values are occasionally met randomly when converter currents drift to a synchronized state.

The maximum current peak is the sum of the maximum current peaks of the individual units (three pulse or six pulse)

$$i_{pp_max} = i_{pp_max1} + i_{pp_max2} + \dots + i_{pp_maxn}$$

The probability that the ripple current value at an arbitrary instant of time is less than 60% of the maximum value is 91.8% for two independent converters. This means that 91.2% of the time the current is less than 60% of the max current. When also the negative peak value is considered, the current ripple stays inside 60% of the maximum ripple 84% of the time. The respective figures for three and four independent converters are 92.4% and 96.3%.

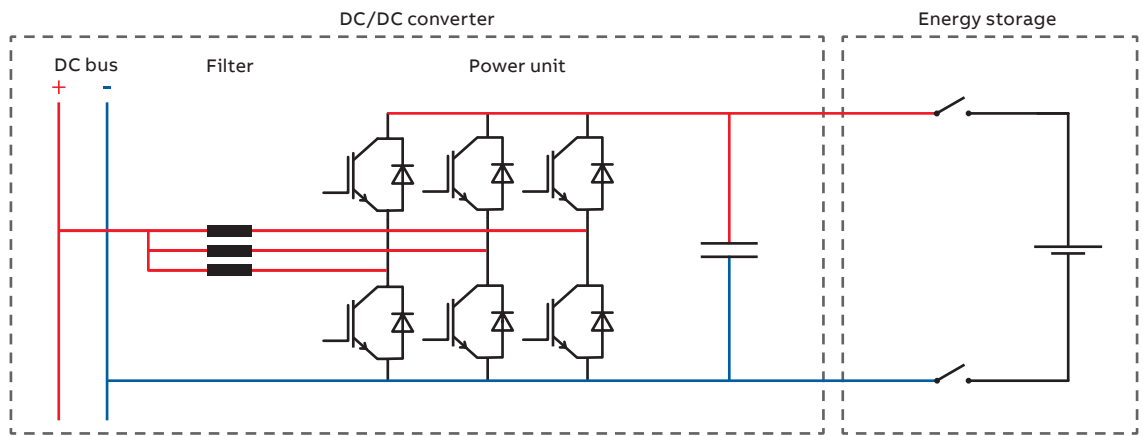
The duration of the synchronous state is random in the frame defined by the clock pulse accuracy of the processor and the carrier frequency of the converter. The probability for the ripple currents of all the independent parallel converters to stay in a synchronized state can be given in function of time as presented in Figure 32. The figure is based on a clock pulse accuracy of 20 ppm. The used synchronous criteria is that at least one of the converters has reached in that time 25% drift in relation to the other converters.

As an example we can see in Figure 32 that the probability for two drives to stay in a synchronous state for 10 s or longer is 4.70%. If we have three parallel connected independent drives, the corresponding probability is 0.22% and for four independent drives it is only 0.01%.

Due to the small probability and short duration of the synchronous state it can generally be assumed that the current ripples of the parallel drives are non-correlated. The individual current signals of non-correlated drives maintain their power. This means that the RMS value of the peak current is the square sum of the components

$$i_{pRMS} = \sqrt{i_{pRMS1}^2 + i_{pRMS2}^2 + \dots + i_{pRMSn}^2}$$

Figure 33:
DDC output
inverse-connected
to DC-bus



3.3.4. Inversed Buck and Boost converter

It can be worthwhile in some cases to use batteries with higher voltages than the one of the DC-bus. This can be done by connecting the output of the DDC to the DC-bus voltage instead of that of the ES, as shown in Figure 33.

To ensure a safe and reliable operation of the converter in this mode the system must be designed so that the battery voltage does not exceed the maximum voltage of the DDC. In inversed connection the output voltage must be measured by an additional unit (BAMU), the ACS880 DC/DC converter measures internally only the input voltage, which is in inversed connection on the battery side.

In inversed connection the battery voltage can never (when connected) be lower than the voltage of the DC-bus. When battery voltage decreases to the level of the DC-bus voltage, the feedback diodes of the IGBTs become conducting.

The galvanic connection of the ES to a DDC can only take place safely if the following conditions are met:

- Battery voltage must not exceed the maximum allowed voltage of the DDC hardware, which can be found in ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644) and ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631).
- The capacitors in the DDC modules must be charged before connecting the ES to the DDC to prevent the inrush current peak.

The ES minimum discharge voltage level is defined by the system designer. Typically, this voltage is lower than the rated DC-bus voltage and thus defines the minimum voltage in the DC-bus. This must be considered in the dimensioning of the motor drives, supply units and supply transformers.

Limitation to the minimum ES voltage

In an inversed connection the feedback diodes prevent the minimum voltage level of the ES to be lower than the voltage level in the DC-bus. If discharging continues after the voltage of the ES has reached the level of the voltage in the DC-bus, then the DC-bus voltage starts to follow the ES voltage. However, due to the diodes in the supply converter, the DC-bus voltage cannot decrease below the amplitude of the AC voltage. The direction of the diodes also means that the ES cannot be charged from a no-charge state to the operation area with the inversed DDC. It always needs to be pre-charged.

This is the fundamental limitation which must be taken in consideration in dimensioning the system.

3.4. Starting up

3.4.1. Basic principles

There are a few basic requirements, which have to be satisfied when designing the system:

1. **The start-sequence must be controlled by a PMS.** The system and its starting sequence can be arranged in several different ways depending on the application design. The starting sequence must adapt to the application, which is why it has to be done in the PMS.
2. **Converter inbuilt capacitors must be charged before connecting the ES to the DDC.** This is important to avoid the destructive inrush current during connection. A good design practice is to ensure successful charging by using interlocking.
3. DC-capacitors in the ACS880-modules are equipped with discharging resistors. **The DC-bus must be disconnected from the energy storage if it is intended to have the charge stored while the converter is idle.**

3.4.2. Charging of the capacitors in standard DDC

As can be seen in Figure 34, the feedback diodes conduct current from the ES to the DC-bus in the DDC. To prevent the inrush current, the DC-bus capacitances must be charged to the same voltage or higher than the ES.

There are two possible starting sequences for the DDC:

1. **DC-bus charged from ES**
If the ES voltage is higher than the DC-bus voltage an external charging unit as illustrated in Figure 34 is required to equalize the voltages. Charging of the DC-bus capacitors can then be finalized by running the DDC in voltage control mode. The prerequisite for charging is for the voltage of the ES to be over the minimum operation voltage given in the ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).
2. **DC-bus charged from AC**
The capacitors in the DC-bus can also be charged with the AC supply unit from the AC grid or generator. Then the voltages of the DC-bus and of the ES must be equalized before connection of the ES.

Finally, the DDC can be started when the DC-bus is charged, and the ES is connected to the converter.

The converter can charge a super capacitor ES from zero voltage. However, the current is discontinuous at very low voltages. Continuous operation under the minimum DDC voltage is not allowed. (See ACS880-1607 DC/DC converter units hardware manual 3AXD50000023644).

Figure 34: The Energy storage with the charging circuit for the converter capacitances and the DC/DC converter

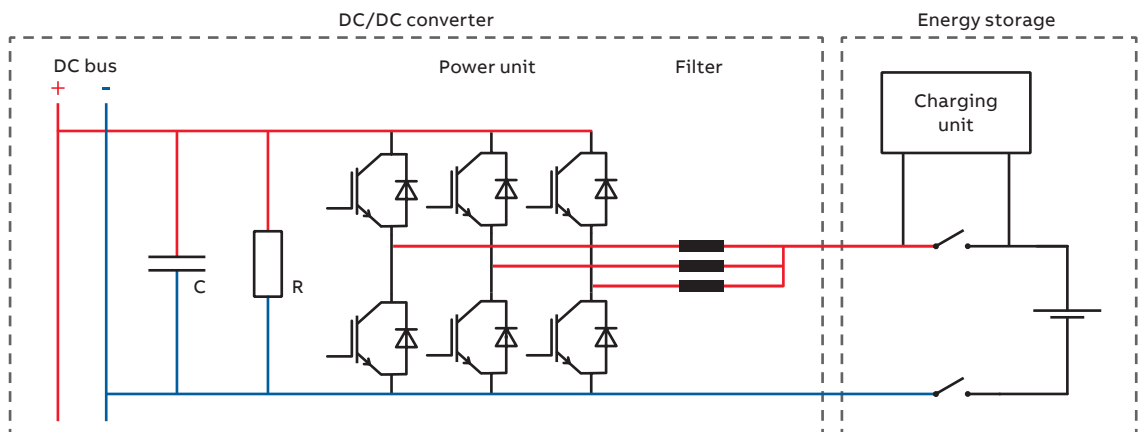
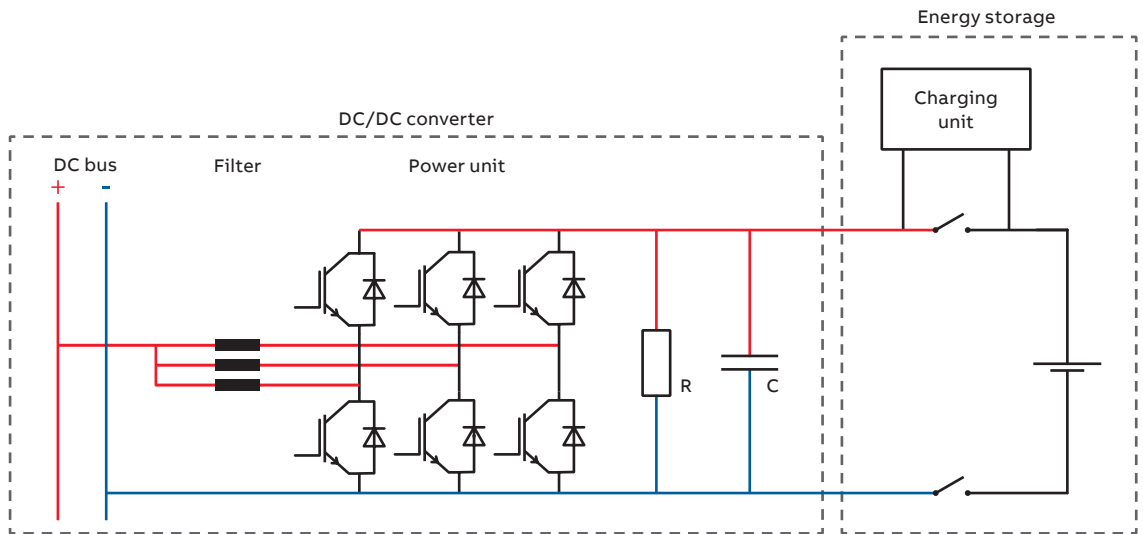


Figure 35:
Inverse connected
DDC and charging unit
for capacitors of the
converter modules



3.4.3. Charging of the capacitors in inversed connected DDC

Figure 35 presents the main circuit of an inverse connected DDC. In this connection feedback diodes conduct current from the DC-bus to the ES. In order to avoid inrush current during the connection of the ES, voltages of the filter capacitors (C) inside the modules and the ES must be equalized.

There are two possible starting sequences for the DDC:

1. DC-bus charged from ES

If the voltage is higher in the ES than in the DC-bus then the DC-bus can be charged from the ES. This requires an external charging unit as illustrated in Figure 35.

2. DC-bus charged from AC

The capacitors in the DC-bus can also be charged with the AC-supply unit from the AC grid or generator. Then the voltages of the DC-bus and the energy storage must be equalized before connection of the ES.

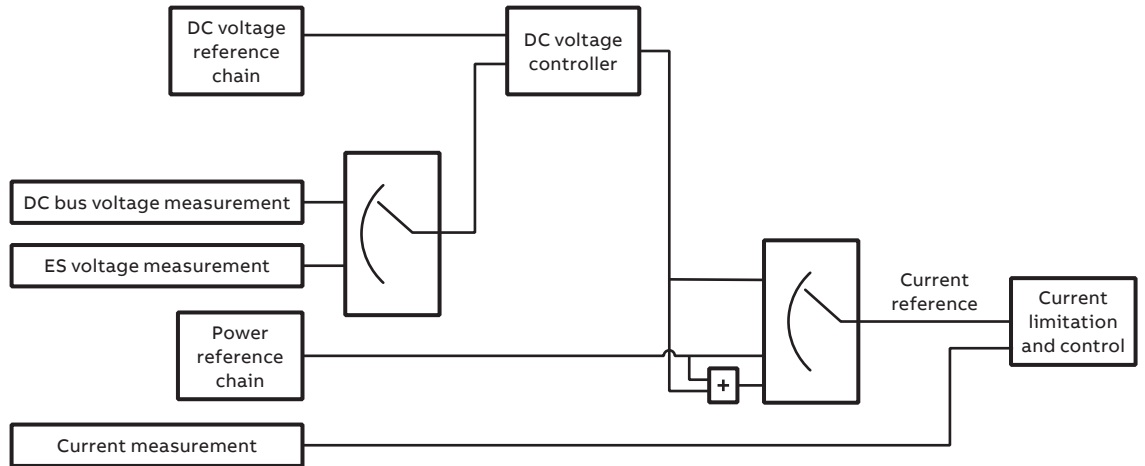
The DDC can be started when the DC-bus is charged, and the ES is connected to the converter.

Charging a discharged supercapacitor unit from the DC-bus requires the connection of the DC-bus to a strong supply (typically the AC grid) through a supply converter. The charging circuits of a DC-bus cannot be used for charging the supercapacitor, as they are usually not designed to withstand the charging current of the supercapacitors. It is also required that the charging unit used to equalize the ES voltage and the output voltage of the DDC is dimensioned for the charging current of the ES.

3.5. Control modes

The DDC can be operated either with power or voltage control. The selection of the desired control mode can be done by parameter as presented in Figure 36.

Figure 36: The selection between voltage and power control



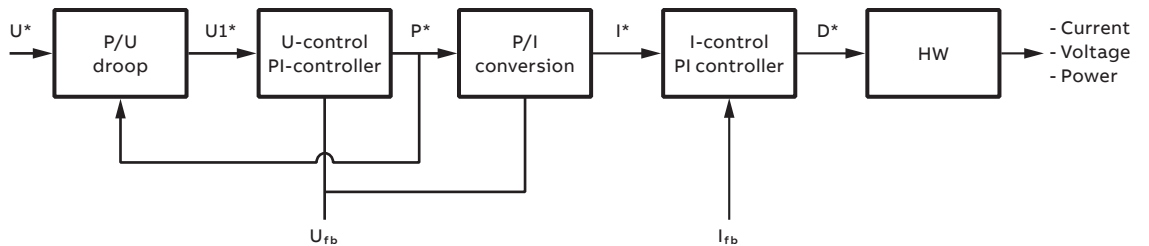
DC voltage control mode

The principle of the control chain of the DDC is presented in Figure 37. The reference values are noted with an asterisk. The notations are:

- U* Incoming voltage reference
- U1* Voltage reference after drooping
- P* Power reference

- I* Current reference
- D* Pulse ratio reference
- U_{fb} Voltage feed back
- I_{fb} Current feed back
- HW Hardware including load

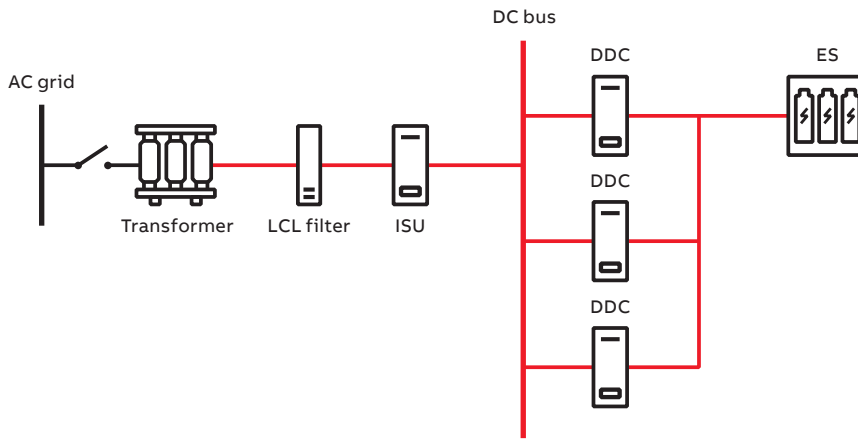
Figure 37: Control chain of the ACS880 DC/DC converter



The voltage controller (including droop control) can be used to control the voltage of either the energy storage or the DC-bus. There is an inbuilt voltage measurement circuit in the converter module for the control of the DC-bus voltage. However, an auxiliary measurement unit (BAMU) is necessary when voltage control mode is used to control the ES voltage.

The ACS880 DC/DC converter does not have an inbuilt measurement circuit in the output of the filter unit, but BAMU measurement units which can be used for this purpose are available as an option.

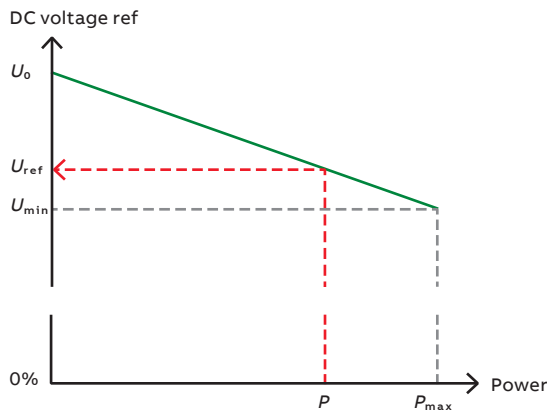
Figure 38: An example of three ACS880 DDC converters connected in parallel to supply the same ES. The inbuilt function in the ACS880 DDC for load sharing between converters in this kind of application is droop-control.



Droop control is a commonly used control method for load current sharing between independently controlled power supplies in the applications as presented in Figure 38.

DC droop control linearly reduces the output voltage when the output power increases as illustrated in Figure 39.

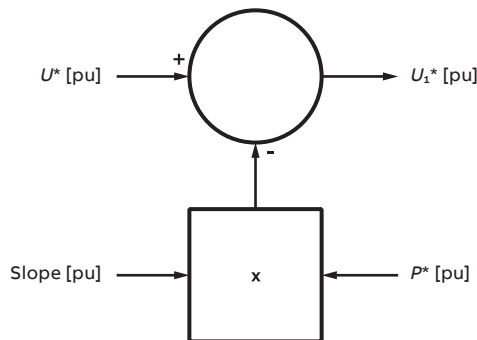
Figure 39: Generic principle of P/U droop-control of the DC-voltage



As Figure 39 illustrates, the output voltage is the no-load voltage U_0 from which is subtracted the product of the slope and power, $U = U_0 - P \times k$. In the ACS880 this is implemented by reducing the reference value of the voltage controller with the product of the slope and the power as shown in Figure 40.

The general limitation caused by the working principle of droop control increases the DC-bus voltage deviation with the load. To optimize the dimensioning of the other power electronic equipment connected to the same DC-bus, especially DC to AC converters, the level of the DC voltage has to be kept inside these comparatively small tolerances. To keep the DC voltage at the desired level it might be necessary to compensate the changes in DC voltage by controlling the DC voltage reference using a PMS or other external controller.

Figure 40: The droop control in the ACS880 DC/DC converter. $U_i^* = U^* - P \times k$



Power control mode

This mode is used when the PMS controls the charge or discharge of the ES.

There is also the option to give current reference instead of power in the DDC control software. When power or current reference values are positive the energy is transferred to the positive terminal of the ES. With negative reference values the energy flows in direction of the DC-bus.

3.6. System control

The control of an ESS operates under the overall ship power management system (PMS). The converters provided by ABB Drives work as a subsystem as shown in Figure 41.

The PMS communicates with the BMS which is a part of the battery protection system and gives information about the state of the battery to the PMS.

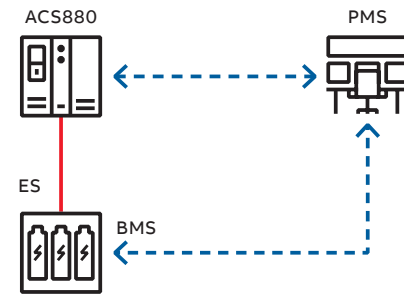


Figure 41:
Basic principle of ES system control

3.6.1. Control of the charge of the energy storage with DC/DC converter

Proportional Integral (PI) control has several features such as simplicity, robustness, and lack of steady state error between reference and feedback, which have made it the most used control method in the industry. PI control works well when the voltage (or the current) of a certain point is controlled by a single controlled power source. This kind of control is used for example in regenerative motor drives. In these applications DC voltage is controlled by an ISU and the motor speed (or torque) is controlled by an INU. The motor drive is seen by the DC-voltage control as a disturbance, which requires robustness from the control. Even though the drive supplies power to the DC circuit in certain operation conditions, it does not control the DC voltage and thus does not override the DC voltage control of the ISU.

PI control is less suited to the cases where two DC voltage controllers are connected to the same point. If two PI controllers try to control the same variable (e.g., the voltage in the same point) the system becomes unstable. In this case even the slightest difference in the feedback signal or the reference causes the outputs of the controllers to drift to the opposite direction until one of the controlled converters runs the maximum current and cannot supply any longer. For this reason, the use of the several DC voltage-controlled converters with their own PI controllers is not an appropriate solution.

The conflict between the controllers can be solved by using droop control instead of PI control. The main advantage of droop control

is that parallel supply units adapt to each other, even though they are controlled independently. The downside is the steady state error in the DC voltage caused by the load dependency of the output voltage. This error is often corrected by the PMS giving a sufficient offset term, which moves the droop curve according to the voltage level.

Another way to solve the conflict is to use a common voltage controller, which gives power, torque, or current references to the individual supplies. There are in modern control theory numerous different Single Input Multiple Output (SIMO) control principles that can be selected. However, DC voltage control requires a relatively high bandwidth, and the use of external controllers is often impossible due to lagging access to the controlled signals.

Below are presented a few examples of applications and their controls.

Peak-shaving for occasional overloads

Generally, when the load in the AC grid increases over a preset limit, the PMS starts an additional genset to ensure the sufficiency of the power supply. In the grids, where the load strongly varies, this can lead to frequent starting and stopping of the genset which significantly shortens the maintenance interval and should be avoided. A cost-efficient solution is to equip the AC grid with a static converter and ES, which is dimensioned to cover around a third of the genset power. Starting and stopping the ES does not impact its life length.

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Figure 42:
Peak shaving
occasional overload

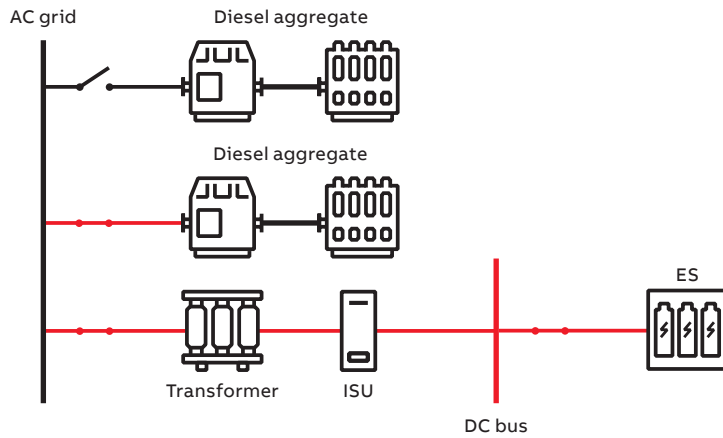


Figure 42 presents an application with a DOL connected ES. In this application the voltage level in the DC-bus is defined by battery charge. To be able to adapt to the power demand of the AC grid, the ISU is operated in AC control mode (OGC operation with P/f and Q/U droops). The charge state of the battery is controlled by manipulating the droop offset by the BMS through the PMS.

Note that the battery current limitation must be arranged by reducing the load in the grid.

Peak-shaving for heave compensation

Heave shaving is a special case of winch/crane applications where the impact of the waves is compensated by winding and unwinding, keeping the velocity of the lifted/lowered subject constant despite the waves. Heave compensation causes a pulsating load component which is added to the static load component.

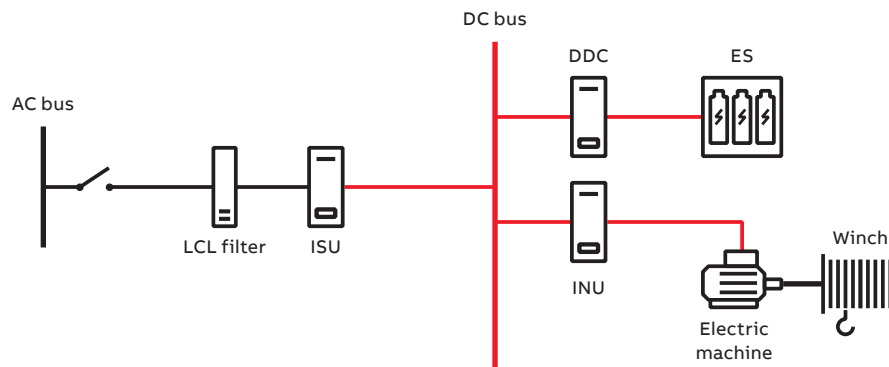
Modern heave compensation applications are equipped with super capacitor ESs to store and supply the alternating load component while

the current in the AC supply is kept steady. The capacitor power flow is relatively high but short lasting (~10 s), leading typically to the selection of supercapacitors for the ES.

The control of a heave compensated winch requires an upper-level heave compensation control unit to calculate the required adjustments. This unit collects the necessary information, starts, and stops the DDC, calculates and gives the references required by the INU and the DDC. The heave control unit is not a part of the ABB system drives product portfolio and scope.

Figure 43 presents a winch application with a DDC connected ES and heave compensation. In this application the operation of the winch motor is speed controlled and the DDC converter operates in power control mode. Both get their references from the heave compensation control unit. The ISU takes care of the DC voltage control with the PI-controller. The charge of the capacitor bank is controlled by the BMS and the heave compensation unit through the DDC converter.

—
Figure 43:
Peak shaving heave
compensation



All-electric vessels

In an all-electric vessel, the majority of the energy flow takes place in the DC-bus, to which are connected both the ES and the main propulsion. The AC hotel load is supplied by the OGC through the transformer, which enables the supply of reactive loads and prevents the common mode harmonics that pollute the AC grid. The hotel load is typically significantly lower than the propulsion load and thus the transformer can be dimensioned with this in mind to a relatively small power.

The ISU is used to charge the battery and to supply the hotel load when the vessel is in port, but it is not running when the vessel is in operation. During the ship's operation the battery is the only energy source.

Note that all-electric vessels are often equipped with emergency gensets, which are not illustrated in Figure 44.

Figure 44 presents a distribution arrangement for a typical electric vessel. In this application charge control is done by the ISU in power control mode, which receives its reference from the BMS through the PMS. The INU is operated either in speed or torque control mode. Enabling the limitation of propulsion power from the BMS and/or PMS is often useful. In AC control mode the OGC is droop controlled.

The operation modes of converters are set by the PMS which manages the switches between charging and discharging modes.

In charging mode, the ISU is connected to the shore grid. Charging is controlled by the BMS, and the ISU is power controlled using references from the BMS/PMS. The OGC supplies the hotel load, and the motor drive is switched off.

In discharging mode, the ISU is disconnected from the shore grid and the motor is running. The OGC supplies the hotel load, and the battery supplies the DC-bus.

In both modes the DC voltage is defined by the battery's charge.

- Change of state between charging and discharging
 - Operation modes of converters are set by PMS
- Charging mode
 - Shore supply is connected to charging ISU
 - Current supply is controlled by ISU, which is operated in power control mode or in DC-voltage control mode
 - Charging is controlled by BMS and PMS
- Discharging mode
 - Motor is running
 - Hotel load is supplied by the ISU, which is operating as OGC (in AC control mode)
 - Battery supplies the DC-bus.
 - DC-voltage controlled by the DC/DC chopper

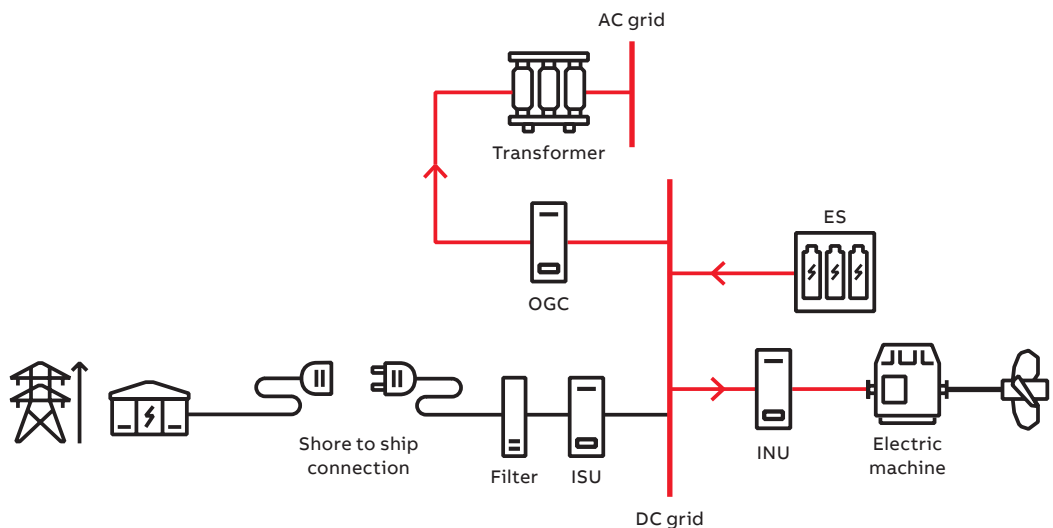


Figure 44: A micro grid with energy storage

Electric propulsion

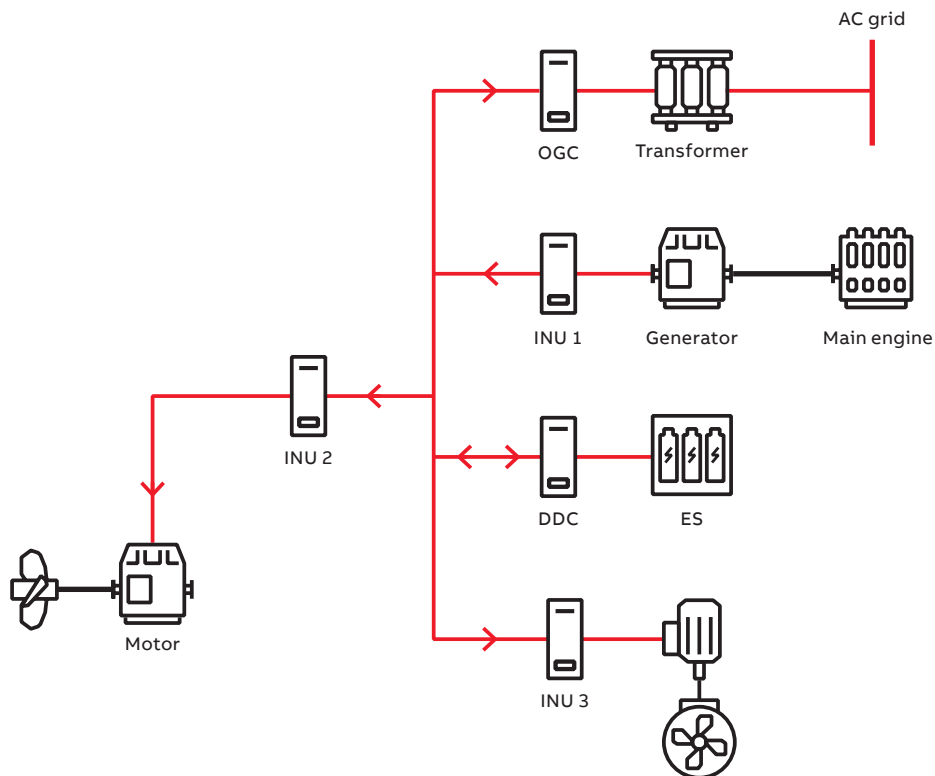
The power supply for electric propulsion can be arranged in several ways. Figure 45 presents one option, where the main engine driven generator supplies the DC-bus through INU 1.

In this example DC voltage is controlled by the INU 1, which can be operated PI controlled or droop controlled. The DDC is operated droop controlled in DC-bus-voltage control mode. This enables

seamless continuity of the DC power supply in case the power supply through INU 1 fails.

The charge control of the battery is managed by the BMS through the PMS. The PMS gives the DDC droop controller a voltage reference, which defines both the power and direction of the battery current as explained above in section 3.5 “Control modes”.

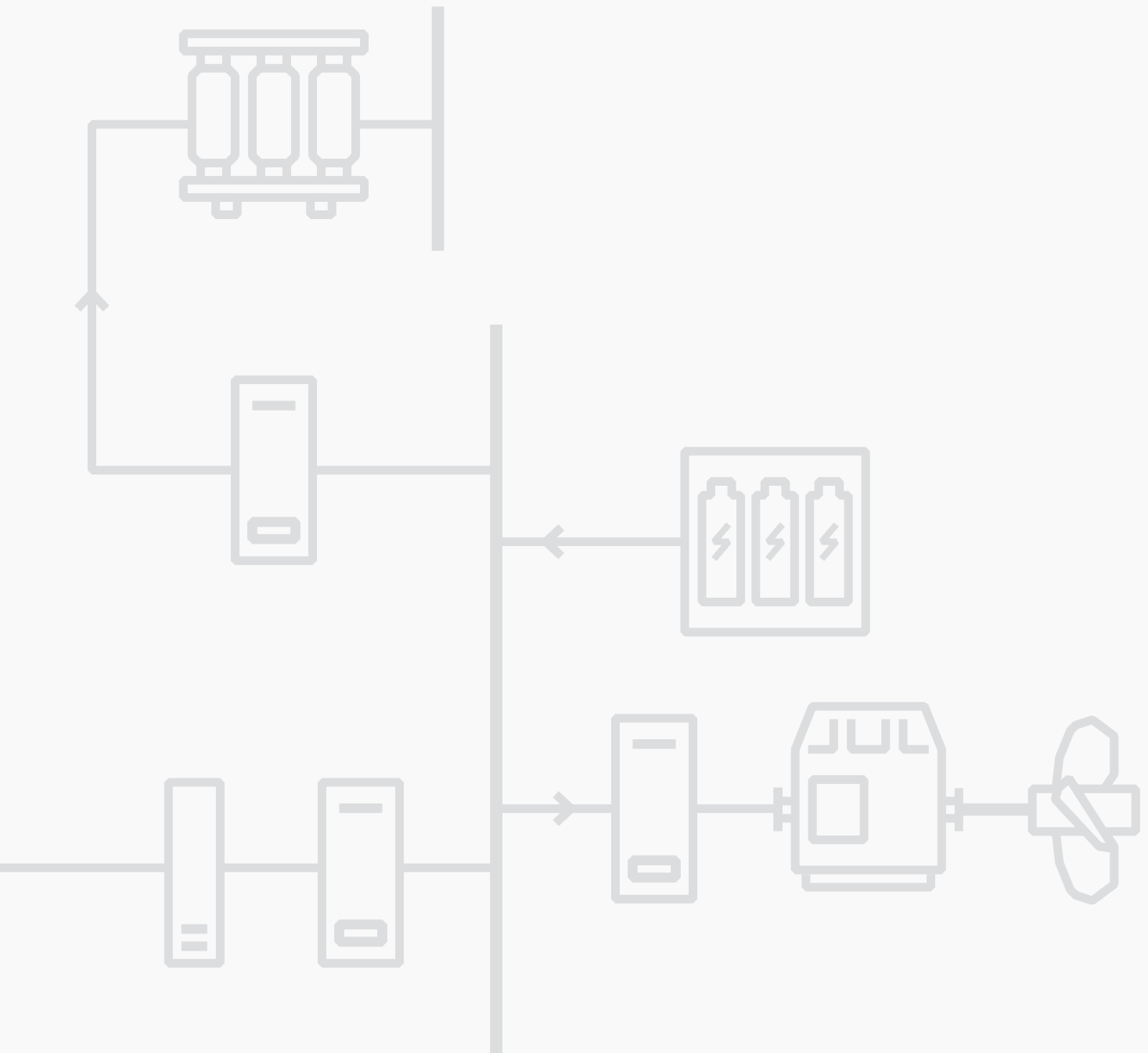
Figure 45:
Electric propulsion



4. Dimensioning

4.1. Contents of this chapter

In this chapter the factors influencing the dimensioning of an ES-converter system for a marine vessel are presented. The considerations will guide you in the process of selecting the ideal solution and products for your needs. In addition to the dimensioning of the ESS, other design issues such as control and protection are discussed in chapter 3.



4.2. DC/DC converter (DDC)

This section outlines the procedure for the selection of a DC/DC converter. In addition, it goes over of a few basic issues related to currents and voltages. All these are explained in more detail in chapter 3.

Selection of a DC/DC converter

The selection of a DC/DC converter for a given ES follows these steps:

1. Selection of a cooling medium (air cooling or liquid cooling).
2. Selection of the DC-bus voltage.
3. Selection of standard or inversed connection based on ES voltage and DC-bus voltage.
4. Selection of the converter based on the current.
5. Checking the current ripple requirements and possible need for an output capacitor.

DC-bus voltage vs ES-voltage

The selected DC-bus voltage must be high enough to ensure the designed performance of the motor drive and the grid converter.

In standard connection the DC-bus voltage must be higher than the ES-voltage in all operation conditions. Respectively in inversed connection the ES-voltage must be higher than the DC-bus voltage. The impact of the voltages on the behavior of the system is explained in section 3.2.

Output voltage range

The desired operation voltage area must be crosschecked against the operation voltage area of the selected converter type. The output voltage area is given in the HW manuals “ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644)” and “ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631)”.

Power and current; current defines the converter

The dimensioning of the semiconductors is based on load current; thus, the maximum current must

be derived from the load power and the voltage. The current in the DDC is different between input and output, however it retains its power (output power is same as input power). The higher of these currents in a standard DDC is the output current (current on the ES side) and in an inversed connected DDC it is the input current (current on the DC-bus side). The higher current always defines the dimensioning of the DDC.

The DDC module can withstand overload for a short time. The exact values for acceptable overloads and cycle times are given in the ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631) and ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).

Parallel connection of the DDC modules is required when the requested output current is higher than the one allowed for the biggest DDC available.

Current ripple and discontinuous current

The values for the maximum current ripples are given in the rating data tables in the following manuals:

- ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644)
- ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631).

The ripple can be reduced by filtering the output voltage and thus also the current with an external capacitor as instructed in subsection 3.3.2.

When the output current is smaller than the peak-to-peak value of the current ripple it will become discontinuous. The discontinuous current worsens the control and the response of the controlled system.

Current ripple is discussed more thoroughly in subsection 3.3.2.

4.3. Direct Online (DOL)

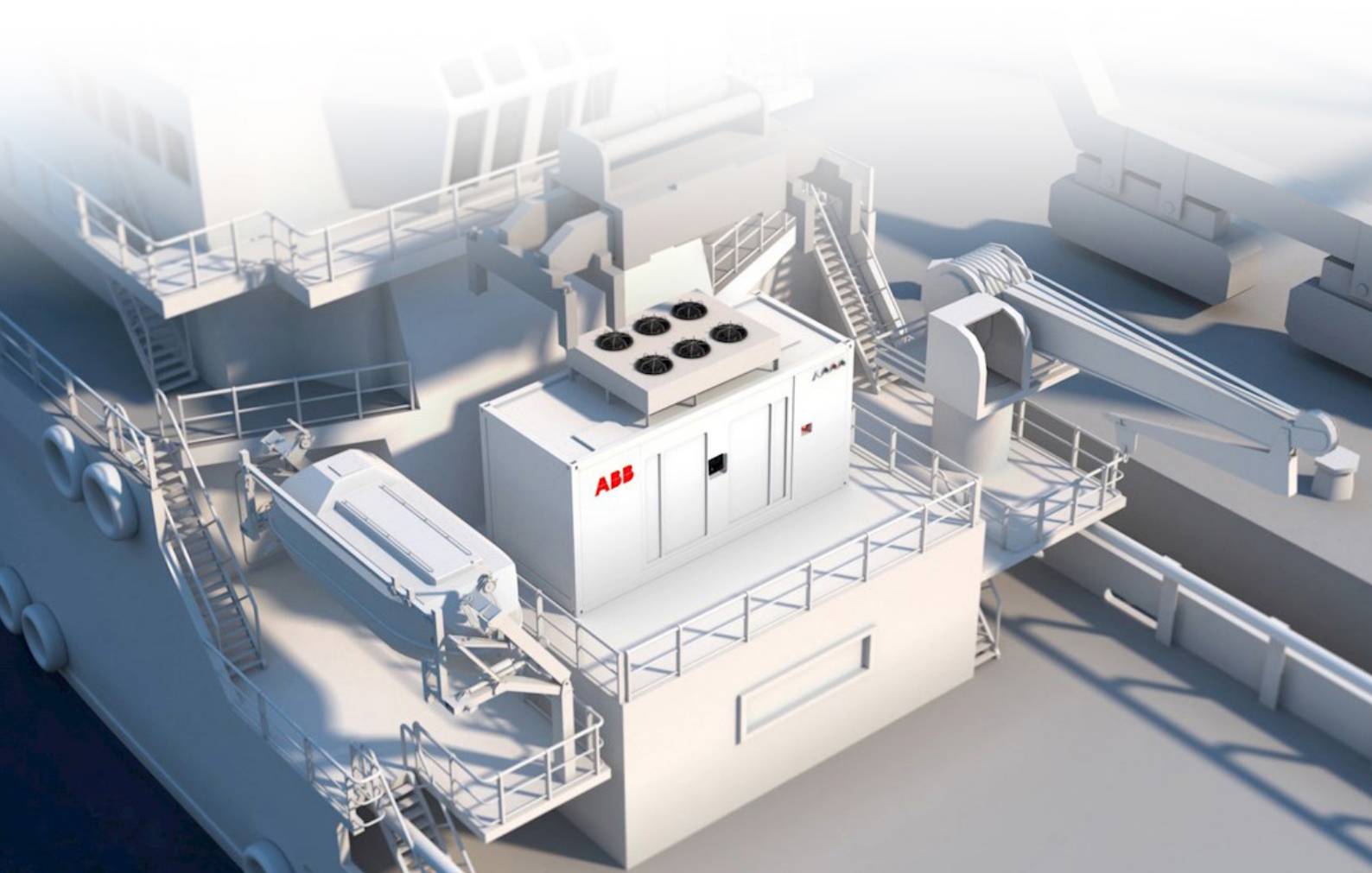
4.3.1. Connection cabinet

DOL energy storages are intended to be connected to the DC-bus with an “ACS880-7107LC DC feeder unit”. You will find the instructions for the selection of the cabinet and the fuses in the ACS880-7107LC DC feeder units hardware manual (3AXD50000752423).

The rated currents for feeder cabinets are given in the ACS880-7107LC DC feeder units; Hardware manual (3AXD50000752423). The manual also includes the necessary information for the fuse selection for cable protection. Properly selected fuses also limit the short-circuit current supplied from the ES to the DC-bus of the drive.

Circuit breakers and charging circuit. Points of disconnection (often at both ends of the cable) must be defined. The feeder unit cabinet can be ordered with an inbuilt disconnection switch and a charging unit, which are available as options. Before selection or design of the charging circuit see the description of charging with different combinations in subsections: 3.4.2 and 3.4.3

Options. The ACS880-7107LC DC feeder units; Hardware manual (3AXD50000752423) contains an extensive list of options, which are worth exploring during the designing phase.



4.4. Energy storage

The ES are not included in the product portfolio of ABB System Drives; thus, the dimensioning of the ES must be done by an external specialist, which often is the ES supplier.

4.4.1. Battery

Voltage

The battery charge defines the voltage for the whole DC-bus, and it has an impact on the performance and dimensioning of all the converters, which are connected to the same DC-bus. It must stay within the converter system's minimum and maximum operation voltages. When selecting the minimum operation voltage, it is important to check the sufficiency of the DC-bus voltage for motor drives and grid converters.

The inverter units have inbuilt undervoltage controllers to prevent undervoltage trips by utilizing the kinetic energy of the motor and the load to charge the DC-bus. This function normally must be disabled to prevent unwanted braking of the motor.

Capacity, C-rate, etc.

The selection of battery capacity is a challenging process. It depends among other things on:

- Selected battery type
- Ambient temperature
- Maximum current
- Maximum energy
- C-rate
- Desired discharge depth

Also, the maximum available current has a strong dependence on the ambient temperature. For these reasons it is highly recommended to use a specialist and the knowledge of the battery supplier to ensure the correct selection.

4.4.2. Super capacitor

Supercapacitors are typically not used in DOL connections due to the limited usable voltage area in the converter's DC-bus and the strong dependency between the stored energy and the voltage of the capacitors. However, it is possible to use supercapacitors DOL-connected if it is needed.

Dimensioning of the supercapacitors is challenging and requires careful consideration of the following points: ambient temperature, load cycles and their frequencies, as well as maximum current. It is recommended to use the assistance of a dedicated specialist or the supercapacitor provider to ensure that all the necessary conditions will be addressed in the dimensioning. For a rough idea of the procedure you will find below a simplified list giving the steps for dimensioning:

1. Select the voltage area. The area of undervoltage control of INUs must be avoided or the controllers must be disabled.

2. Define the energy need:

$$E = \int_{t_0}^{t_1} P dt = P_{av}(t_1 - t_0)$$

3. Estimate capacitance

$$C = \frac{2 E}{(U_{max}^2 - U_{min}^2)} + C_{res}$$

An additional capacity reserve (C_{res}) should be included to ensure the requested capacitance in different operation conditions throughout the life length of the ES.

4. Define load current.
5. Select the capacitor bank.

5. Summary

5.1. Offering

The DDC is available in both liquid-cooled and air-cooled converters. Its availability is however limited to multidrive and module offerings. The hardware arrangement for the OGC controlled ISU requires fiberoptic communication which use BCU control boards only available in large module sizes.

5.2. Scope of supply

The scope of the delivery of ABB System Drives factory includes the ACS880 air and liquid-cooled products.

The exact scope is subject of commercial negotiations, typically including:

- Converters
- Output filters
- Voltage measurement BAMU 12 (option)
- Circuit breakers (option)
- Charging circuit (option)

The complete list of options is available in the ACS880-1604LC DC/DC converter modules hardware manual (3AXD50000371631) and ACS880-1607 DC/DC converter units hardware manual (3AXD50000023644).

The scope of the delivery by ABB does not include BMS, PMS or any other system level control equipment or software.

5.3. Batteries and Supercapacitors

The main ES types used in ships are batteries and supercapacitors, where the trend seems to be towards Li-ion batteries.

5.4. Connection

The connection of an ES can be done either through a DOL-connection or a DC/DC converter. The protection from current transients and their impact on battery lifetime is the main issue requiring special attention in DOL connection. A quick comparison between these two methods is presented in Table 2.

Table 2: Comparison between DOL-connection and connection using DC/DC converter

	DOL-connection	DC/DC converter
DC-bus	Low minimum voltage level in DC-bus	High minimum voltage level in DC-bus
Utilizable voltage range	Limited	Large
Controllability	Limited	Good
Protection	Overload protection limited	Good
Price and Footprint	Often better (low minimum DC-bus voltage can lead to larger total system)	

5.5. Control

ES control is managed by the PMS and BMS. The BMS monitors the state and condition of the ES, when the PMS takes care of the grid level control (starting, stopping, changing operation and control modes), as well as giving the current or voltage references for the equipment level controllers.

The operation modes available in a DDC are voltage control and power control. For voltage

control either a PI-controller or a droop controller can be used. You can find more detailed information in the subsection 3.2.1, subheading "Control of a DOL-connected energy system".

Converter level ES control in a DOL connection must be arranged by controlling the DC-bus supply for example with an ISU or OGC controlled ISU.

5.6. Dimensioning

5.6.1. Feeder cabinet

The main points to consider in the selection of a feeder cabinet are:

1. Thermal current
2. Number of parallel cables
3. Disconnection of the output

5.6.2. DDC

Voltage

Check the voltage area of the ES in relation to the required DC-bus voltage.

Current

The selection of a DDC is based on the current to be handled. The currents in the output and input of the DDC are different and the DDC must be dimensioned according to the higher one of these two currents.

Disconnection switch and charging unit

Consider the potential need for disconnection in the selection of a DDC and its options. The DDC can be equipped with a disconnection switch and a charging unit if needed.

5.6.3. Charging unit

When the ES connection is equipped with a disconnection switch, it also needs to be equipped with a charging unit to be able to equalize the voltages before closing the switch. Typically, the charging unit can be dimensioned to only be able to charge the DC-bus.

5.6.4. Energy storages

Dimensioning of the ES is a challenging task. Energy storages are not in the ABB System drives scope of the delivery, thus their dimensioning is not detailed in this document, even though some general guidelines are given in subsection 4.4. The dimensioning is recommended to be done by a dedicated specialist, for example the provider of the ES.

Additional information

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