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High Speed Train Propulsion & TCMS Design Production Project

Motor Converter Module (MCM) Design

JDEVS-HPDP-MC-DD-300-00

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DEC 2022

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1. Introduction

Figure 1. shows the main block diagram of propulsion system. The propulsion and auxiliary systems consist of three types of converter boxes, namely Auxiliary Converter and Battery Charger Box (AB box), Propulsion Converter and Auxiliary Converter box (PA box), Propulsion and High voltage box (PH box), and Active Front End Module (AFE Module).

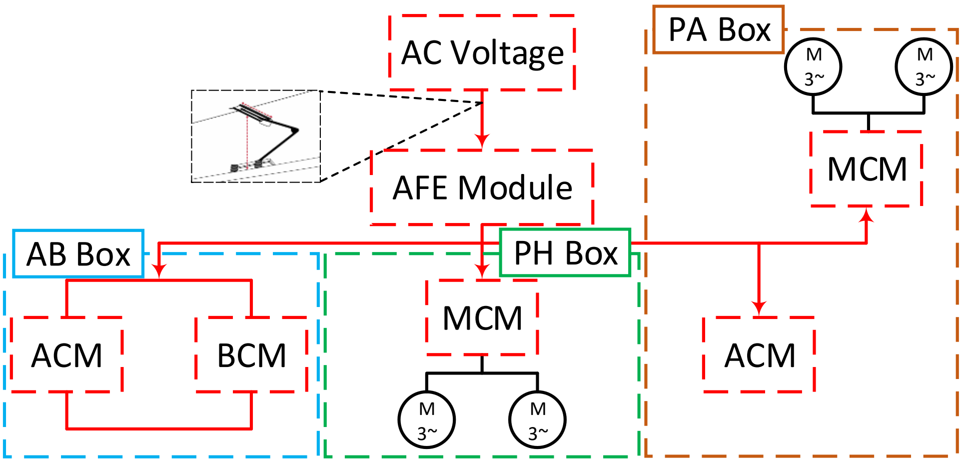


Figure 1. The main block diagram of propulsion system.

1.1. Purpose of this document

The purpose of this document is to give a brief description of Motor Converter Module (MCM) placed in PH Box and PA Box. The document contains general information about the product and its components and both the function and the design of the product are described.

The document is intended to be read as an introduction to the product, by both management and maintenance personnel.

1.2. Acronyms and abbreviations

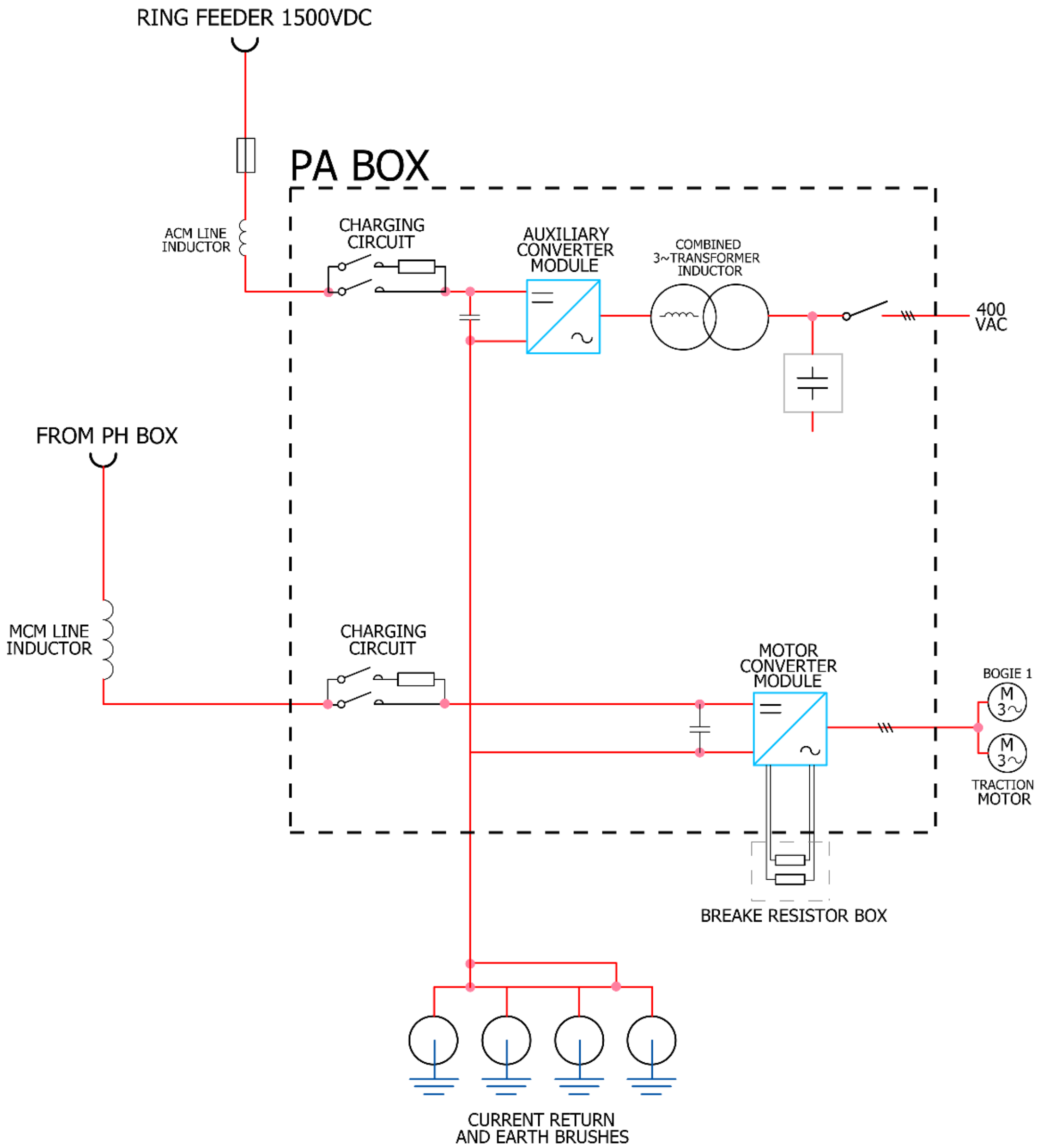
The acronyms and abbreviations used in this document are listed in the below table.

Table 1. List of abbreviations and acronyms

AB	Auxiliary converter and Battery charger box
PA	Propulsion / Auxiliary box
PH	Propulsion / high voltage box
MCM	Motor converter module
BCM	Battery charger module
AFEM	Active Front End Module
ACM	Auxiliary Converter Module
CCU	Communication controller unit
DCU	Drive control unit
DSP	Digital signal processor
FPGA	Field programmable gate array
GDU	Gate drive unit
IGBT	Insulated gate bipolar transistor
I/O	Input/ Output unit LED
LED	Light emitting diode
MCU	Micro controller unit
MVB	Multifunctional vehicle bus
OVP	Overvoltage protection
PSU	Power supply unit
VCU	Vehicle control unit
PWM	Pulse width modulation
SVM	Space vector

2. MCM Overview

The single diagram of PH and PA are shown in Figure 2. As shown in Figure 2, the main part of PH/PA box is MCM, which converts DC voltage into three-phase voltage. The main duty of MCM is to supply and control of traction motors. The input voltage of MCM is 1500 V DC, which is converted to 1287 V AC with variable frequency in order to control the speed of traction motors placed in the propulsion system.



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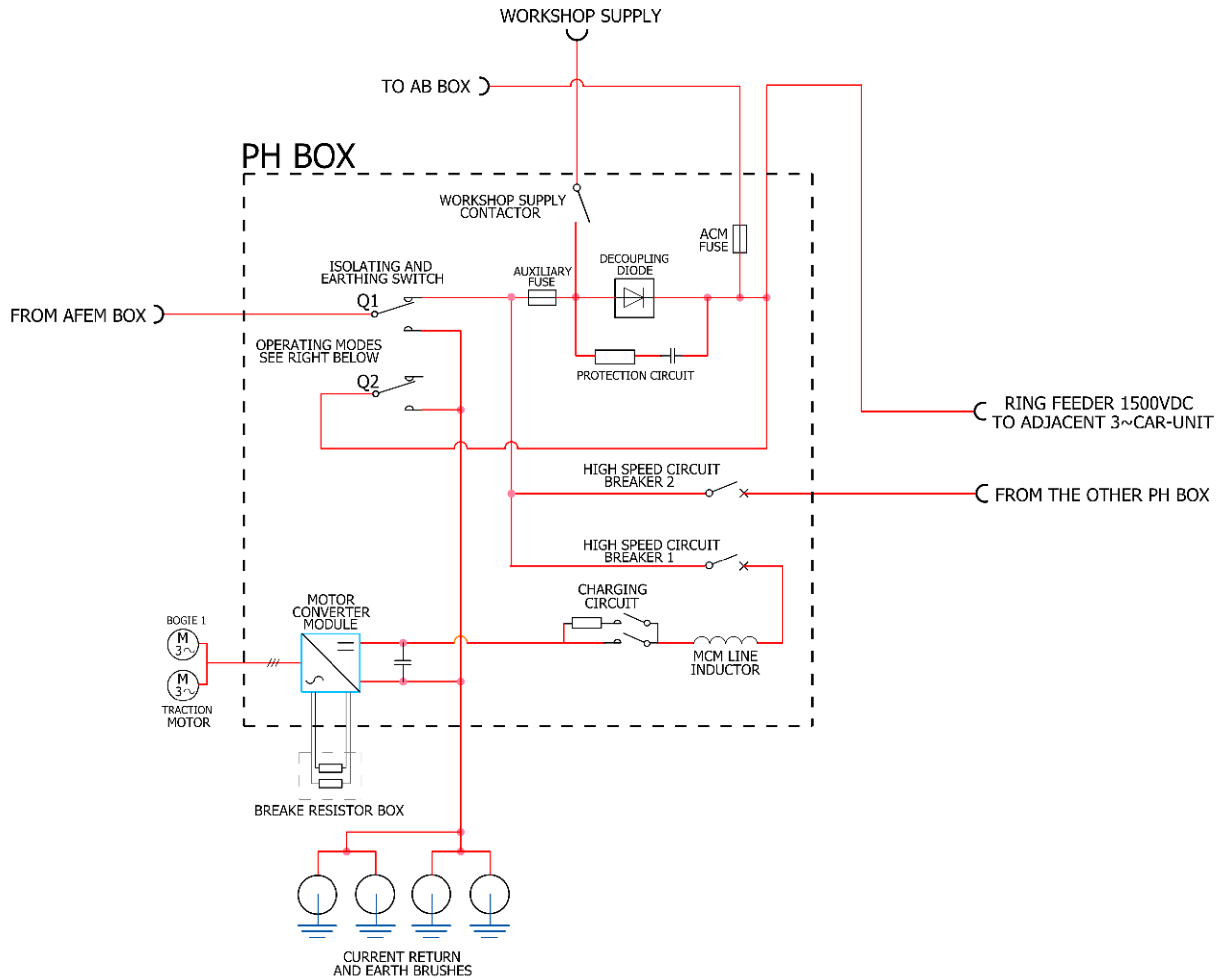

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Figure 2. Single diagram of PH/PA box.

3. Motor Converter Module (MCM)

3.1. General product description

3.1.1. Product introduction

The main function of the Motor converter module (MCM) is to convert input DC voltage to AC voltage. The MCM includes all necessary control functions for the power conversion, with exception of train-level controls.

Electrically, the system consists of the following main subsystems:

- DC link capacitor: Stabilizes the input voltage.

- Three-phase converter: Converts the input DC voltage into three-phase voltage.
- Overvoltage chopper: Protects the converter module from voltage transients. All systems are supervised and controlled by an internal computer. Mechanically, the system consists of the following parts:
- Power section and an electronic unit for high voltage devices.
- Control section with the computers and power supplies.
- Capacitor section.

3.1.2. Software function

This document also describes how the following functions are handled in the converter box software:

- Torque control
- Speed measurement
- Line trip
- Neutral sections
- Fault handling

3.1.3. Illustration

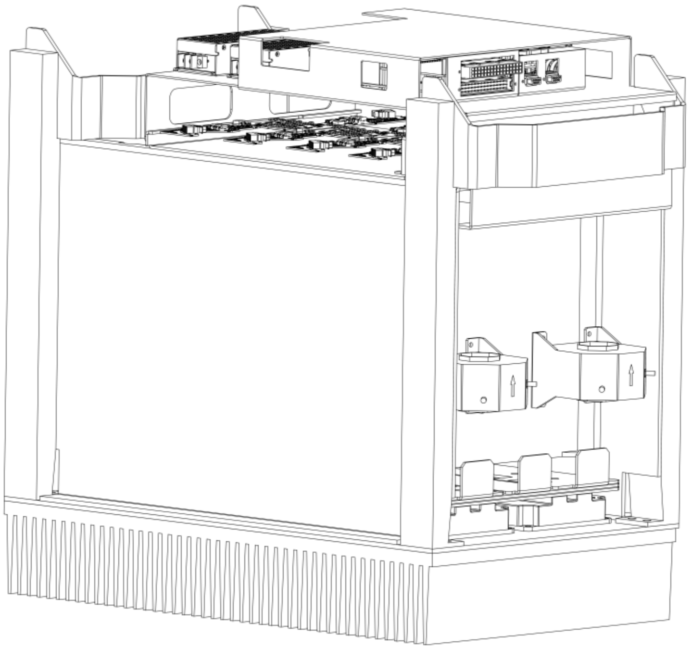


Figure 3. Motor Converter Module (MCM)

3.2. Functional description

3.2.1. Main circuit

The figure below shows an overview of the main circuit and components in the converter module.

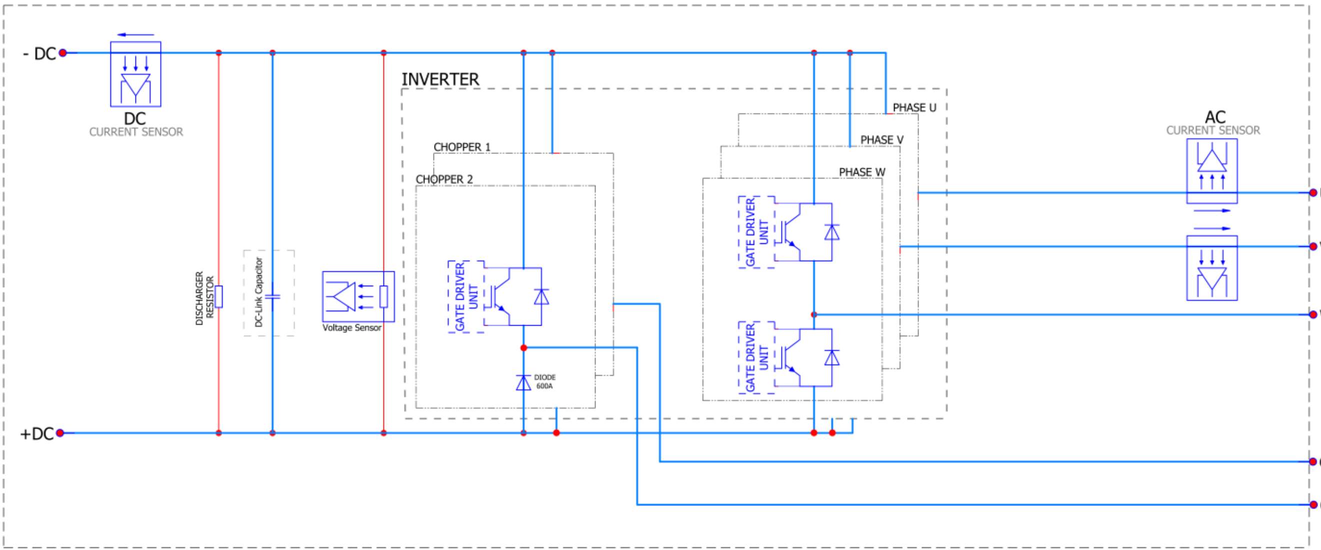


Figure 4. Block diagram of the motor converter module (MCM)

The MCM is based on an insulated gate bipolar transistor (IGBT) and employs three identical phases. Each phase is connected to the DC link in parallel. The IGBTs located in each phase convert the stabilized DC link voltage into a three-phase power with variable voltage and variable frequency, by switching on and off. The produced three-phase power feeds the two traction motors in parallel.

Gate drive units (GDUs) control the switching of the IGBTs and communicate with the Drive control unit (DCU). Status is indicated by Light emitting diodes (LEDs) on the GDUs.

The DCU monitors signals from sensors for temperature, current, and voltage to control the MCM and the converter box. It also switches the overvoltage protection (OVP) chopper if the DC link voltage exceeds the defined maximum value.

The DCU, GDUs, and sensors are powered by a low voltage Power supply unit (PSU). Needless to say that each converter module controls two parallel traction motors.

3.2.2. DC link filter

- **DC link capacitor**

The DC link capacitor is an energy buffer. The capacitor filters and stabilizes the DC link voltage and is sized with sufficient capacitance to keep the voltage ripple in the DC link within permitted limits and enable accurate converter control.

- **Discharge resistor**

There are two discharge resistors connected in parallel with the DC link capacitor. The resistors are connected in series with each other.

In case of failure in the normal discharging sequence, the discharge resistor discharges the DC link to less than 50 V within five minutes.

- **Neutral section**

By using the kinetic energy of the vehicle, it is possible to maintain the voltage across the DC link capacitor during neutral sections.

When a neutral section is detected, the torque reference is momentarily replaced by gentle braking. In braking mode, the three-phase converter has a reversed power flow and power is fed back from the motors to the DC link capacitor. As soon as the supply voltage returns, the original torque is applied.

In this way, the converter module does not have to be reactivated after each neutral section.

3.2.3. Converter function

- **Function overview**

The main task of the motor converter is to control the speed and the torque of the traction motors. This is done by converting the DC link voltage into a symmetrical three-phase power supply with variable voltage and variable frequency, controlled by the DCU.

During electrodynamic braking, the power through the converter is reversed and the energy is converted from three-phase into DC voltage.

The three identical phase legs in the converter; U, V, and W, are shown in the following figure.

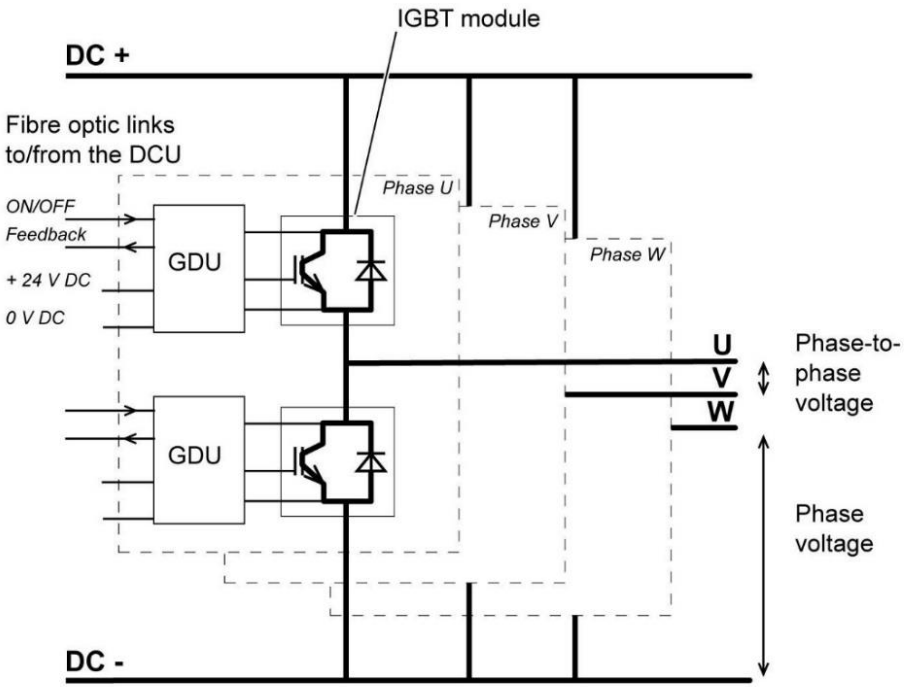


Figure 5. Three identical phase legs in the motor converter module

- **IGBT module**

Each phase leg in a converter has two IGBT modules. Each module consists of one IGBT and one anti-parallel free wheel diode. The IGBT is switched on and off by the GDUs feeding a voltage signal to the gate terminal.

In a motor converter, the switching of the IGBT forces the voltage at the phase outputs (U, V, and W) to alternate between DC+ voltage and DC- voltage. This results in a controlled AC phase-to-phase voltage.

The free-wheeling diode provides an alternative route for the current during turn-off. As a result, the current can flow through an alternative path avoiding IGBT failures due to overvoltage.

During switching, the phase currents will be redirected from the upper to the lower IGBT module, or vice-versa, which is called a commutation.

□ Gate drive unit

There are two GDUs per phase leg, one for each IGBT. The GDU switches the IGBT on and off, based on orders from the DCU. The GDU can also detect phase leg short circuits and send this information, via optical cables, back to the DCU. The GDUs are powered with +15V from the low-voltage power supply. If the GDU detects a loss of the +15V power, the converter is immediately blocked.

The switching orders from the DCU are transmitted via optical cables which galvanically separate the high-voltage system from the control system.

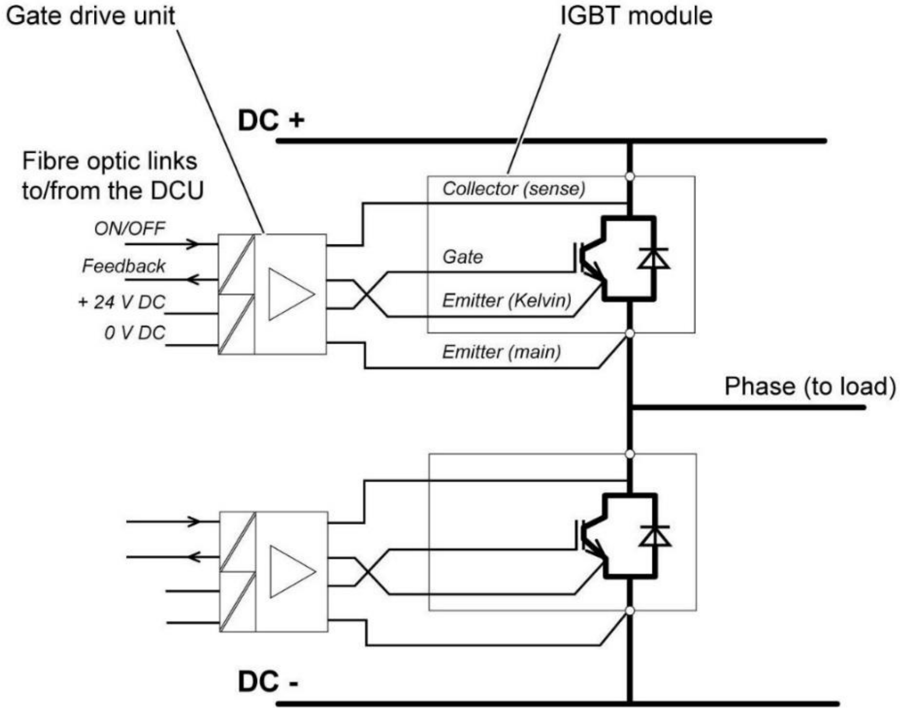


Figure 6. Gate drive unit

A LED mounted on FGU indicates the status of the GDU Power.

□ Phase commutation

When the upper IGBT in a phase leg is switched ON and the lower IGBT is switched OFF, the voltage output in the phase leg is equal to the DC link voltage (DC+), see Figure 7.

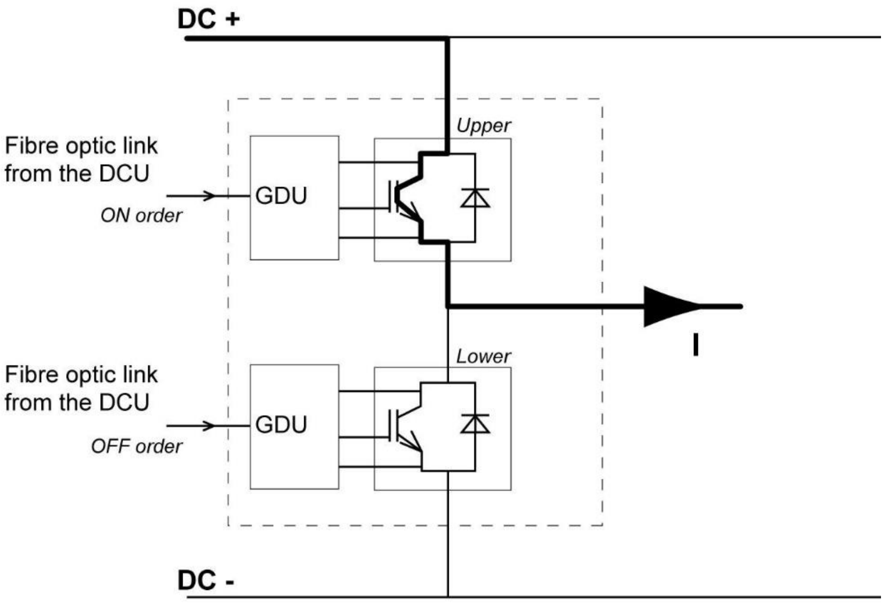


Figure 7. Phase leg conducting mode (positive phase current), a

When the phase leg output is set to low, an OFF order is sent to the upper IGBT and an ON order is sent to the lower IGBT. The phase current will then go through the free-wheeling diode of the lower IGBT module, see Figure 8. The output voltage in the phase leg is now zero volts (DC-).

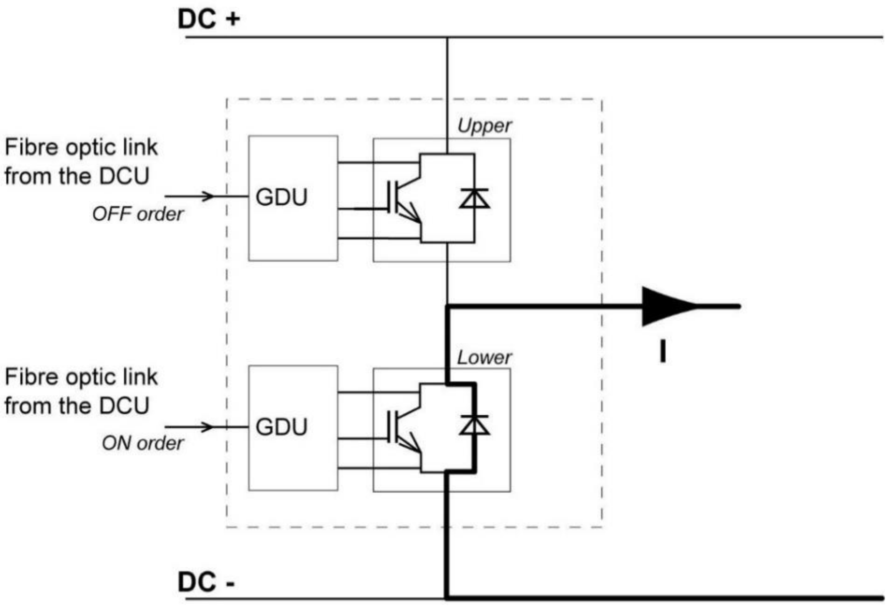


Figure 8. Phase leg conducting mode (positive phase current), b

Since the motor converter function converts the DC link voltage into a symmetrical three-phase voltage, the IGBT that supports the motor converter also handles negative phase current.

In every commutation above base speed of the vehicle (and often below base speed), the current changes direction and commutates from the diode to the IGBT, in the lower IGBT module, and back to the supply DC-. (The current has reversed and the definition is now that the current is negative.) See Figure 9.

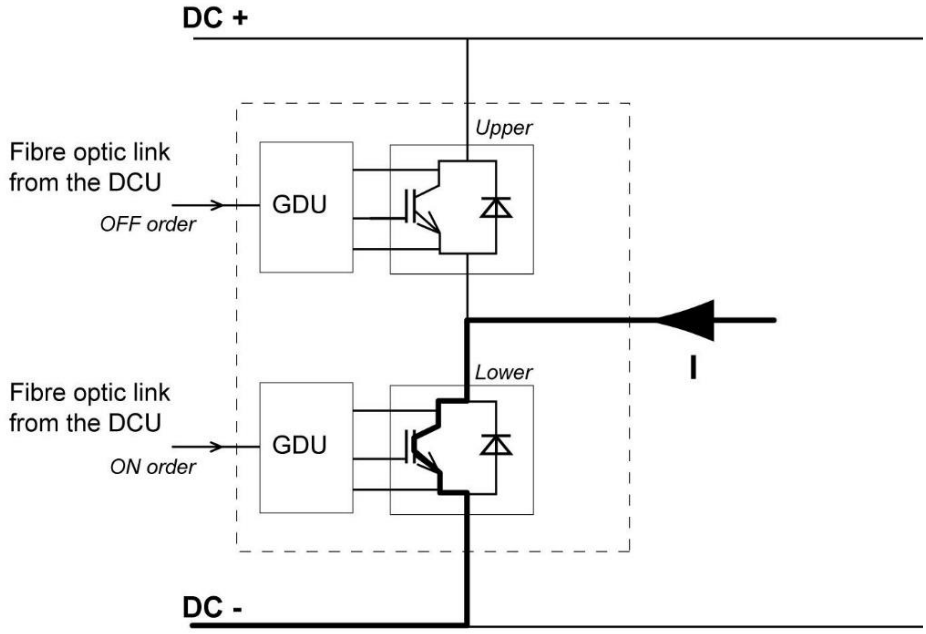


Figure 9. Phase leg conducting mode (negative phase current), c

When the phase current is negative, the current during commutation is reversed. The current commutates from the lower IGBT to the free wheel diode of the upper IGBT-module and back to the load (and is free-wheeling down or forced down.) See Figure 10.

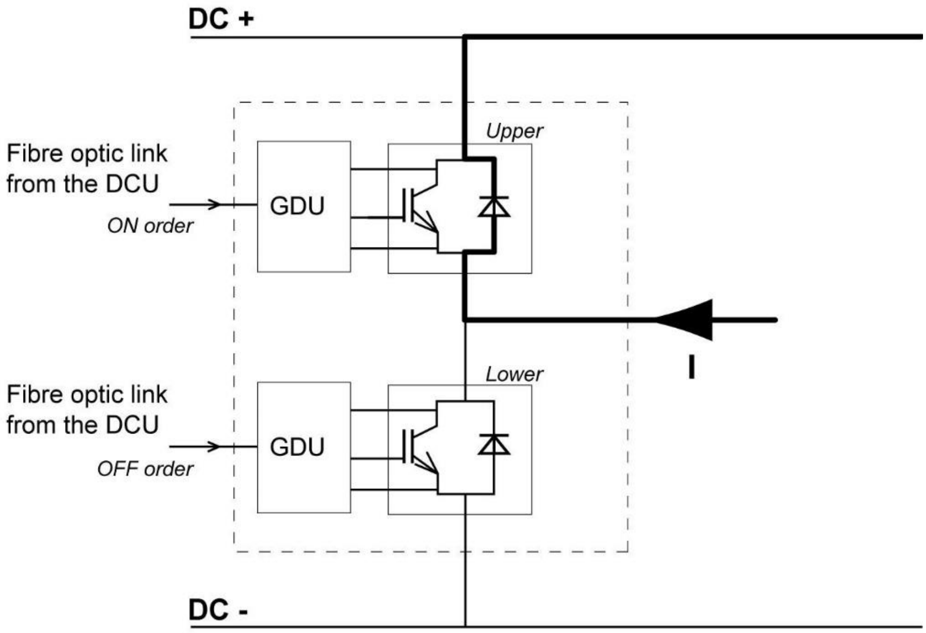


Figure 10. Phase leg conducting mode (negative phase current), d

The current is reversed from the negative direction as shown in Figure 9 and Figure 10 to the positive direction when the upper IGBT is gated on as shown in Figure 7. The commutation cycle is repeated following the same transition sequence.

- **Modulation patterns**

The motor is controlled by the voltage and the frequency of the input power. The variable voltage and frequency are produced using the Pulse width modulation (PWM) technique. The PWM method used in the motor converter is called Space vector modulation (SVM).

The PWM chops the DC link voltage into a three-phase AC voltage, using the IGBTs switching capabilities. This provides efficient motor control and the relatively high switching frequency keeps the motor losses due to ripple as low as possible.

The IGBT switching frequency dictates the ability of the PWM to produce the ideal motor currents. The higher the frequency the less ripple in the motor current, resulting in lower motor losses. Albeit the IGBTs losses increase in this condition and the related requirements should be met.

The motor stator frequency determines the speed of the vehicle, and during normal PWM (up to base frequency) the motor voltage/frequency ratio is constant for nominal flux. As the stator frequency exceeds the base frequency, the motor voltage remains constant as shown Figure 11.

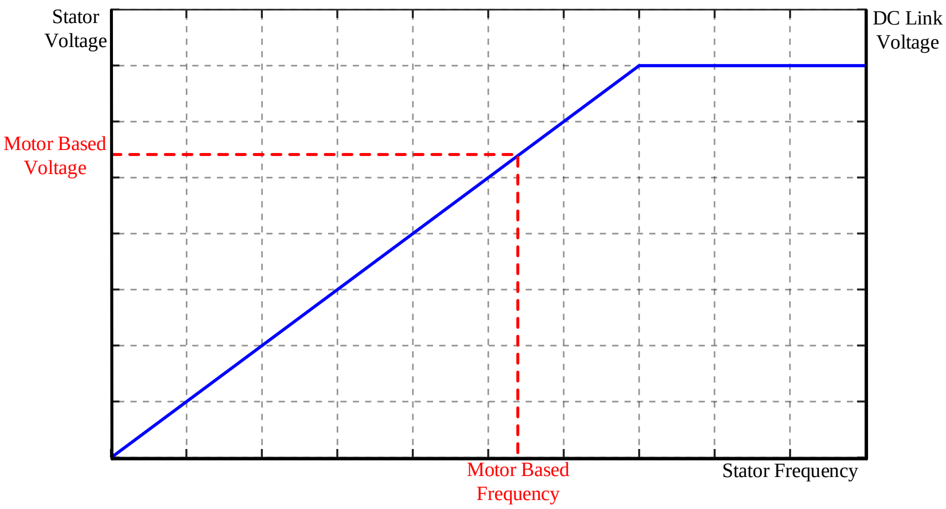


Figure 11. Example of the relationship between stator voltage and stator frequency

3.2.4. Overvoltage protection

- **General**

The brake chopper consists of two identical phases, as shown in the following figure.

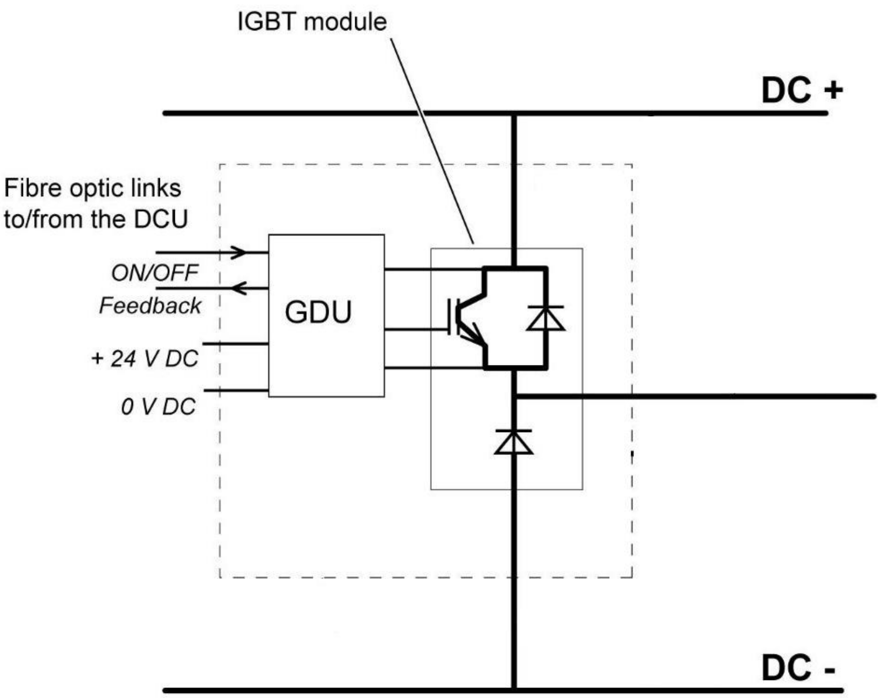


Figure 12. Brake chopper phase legs

- **IGBT module and freewheel diode**

The IGBT module includes an IGBT and two freewheel diodes, one for the IGBT and one for the resistor, which is necessary due to internal inductances.

The function of the IGBT is detailed further in the section IGBT module. There is no lower IGBT in the OVP phase while a free-wheeling diode is inserted to create a current path in case of IGBT is turned off.

- **Overvoltage protection**

The brake chopper protects the converter from overvoltage. The OVP can be enabled in drive, as well as braking mode, and when the electrodynamic braking is disabled.

The phase legs are activated as soon as the voltage across the DC link capacitor exceeds a predefined value. When the overvoltage protection is activated, energy is dissipated in the brake resistors and the DC link voltage starts to drop. When the voltage reaches a predefined level the overvoltage protection is deactivated. The two brake chopper phase legs are activated together in parallel.

- **Electrodynamic braking**

During electrodynamic braking, the chopper is used by the DCU to limit the DC link voltage.

Electrodynamic braking is produced by reversing the power generated by the motors through the three-phase converter and the power is fed back to the line voltage. If the line is not available to receive the voltage for any reason, the DC link voltage increases. At a predefined value, the chopper is activated. The energy from the braking is then redirected by the chopper and is sent to the overvoltage resistors where it is dissipated into heat.

- **Supervision**

The DCU calculates the power through the three-phase converter and the chopper. This power information is used to compare the input power with the output power in the propulsion system. If input and output power differ, a "power balance fault" is indicated. This may be caused by a chopper phase leg being affected by an IGBT short circuit, an overvoltage resistor fault, or a blocked GDU.

The thermal load of the overvoltage resistors is calculated from the power through the chopper. The power dissipation is calculated using the DC link voltage and the modulation index of the chopper. If the maximum allowed resistor temperature is reached, electro dynamical braking is temporarily disabled, and the train will have to use the friction brakes.

3.2.5. Computer

- **Function**

The Drive control unit (DCU) is a local computer that supervises and controls most of the functions in the converter module.

The DCU is both software and hardware. Most of the system controls and protections are programmed in a Microcontroller unit (MCU) and a Digital signal processor (DSP). Some important and time-critical functions are implemented in the programmable hardware called Field programmable gate array (FPGA).

□ **Communications with the vehicle computer**

The following is the most important information that is transmitted between the DCU and VCU and the communication is done through MVB Bus

- Activation order (in)
- DC link voltage (out)
- Line current (out)
- Status (out)
- Fault indications (in/out)
- Speed (out)
- Travelling direction of the vehicle (in)
- Torque reference (in)

□ **Optical cables, inputs and outputs**

There is a circuit board for the optical cables assembled on the DCU. The cables are used for communicating with the GDUs. The optical board converts voltage-based signals into optical signals (light pulses), transmits them through the cable, and at the other end, the signals are converted back to voltage signals.

The optical cables galvanically separate the power circuit from the DCU, thus reducing electrical interference.

No. of I/O	Function
Eight inputs	IGBT status feedback
Eight outputs	Orders for switching of the IGBTs

3.2.6. Control and supervision

□ **Control areas**

The DCU for the MCM has the following functions:

- Charging and discharging of the DC link capacitor, see section Charging and discharging of DC link capacitor.
- Torque control, see section Torque control.
- Speed measurement, see section Speed measurement.
- Temperature measurement, see section Temperature sensors.

- Slip and slide control.
- Overvoltage protection.
- Overcurrent protection.
- Earth fault indication.
- Cooling system control.
- Test functions.
- HSCB control.

□ **Charging and discharging of DC link capacitor**

The DCU has standard functions for the control and supervision of the separation and charging contactors. The train control system initiates the converter start-up by sending a command to the DCU. Provided the converter is in the normal discharged state, with no active faults, and is not blocked, the DCU will start the converter using the separation and charging circuit.

Each converter has one separation contactor, in the DC+ line. The charging circuit consists of a charging contactor and a charging resistor, connected in parallel with the separation contactor in the DC+ line.

During normal converter operation, the separation contactors are closed and the charging contactor is open. During converter start-up the charging circuit is used to connect the DC link to the supply line in a controlled manner, using the charging resistor to limit the inrush currents into the DC link. The actual component being charged is the DC link capacitor which is connected between the DC link poles. When starting the DC link charging, the charging contactor is closed. The separation contactor in the DC+ line remains open. Now the DC link capacitor is slowly charged, with current limiting provided by the charging resistor. When the DC link voltage approaches the supply line voltage, the charging contactor is opened and the separation contactor is closed. Now the converter is ready for normal operation. Normally, a fast DC link discharge is required, using the overvoltage protection chopper. The active discharge is supervised. As a backup, it is possible to slowly discharge the DC link capacitor through its discharge resistor.

Before maintenance work inside the converter, the maintainer must follow the proper instructions for checking and discharging the DC link voltage.

□ Torque control

The DCU controls and supervises the torque produced by the traction motors. The VCU provides the DCU with a weight-compensated and jerk-limited torque reference. The DCU adjusts the reference with respect to wheel diameter.

The torque reference is limited by the DCU with respect to:

- High motor or converter temperatures
- High or low DC link voltage
- High line current
- High axle torque
- Fault conditions

The torque control uses the following measurements for torque calculation:

- Two-phase currents
- DC link voltage
- External DC input voltage
- Axle speed

To achieve the desired motor torque, the motor voltage reference (amplitude, frequency, and phase angle of the phase voltages) is controlled using Pulse width modulation (PWM). The PWM is based on vector references that make the maximum possible use of the DC link voltage, hence maximizing the available torque.

□ Speed measurement

The speed and position of each motor are measured using an encoder and the average axle speed and the linear speeds of all axles are calculated. The calculations are based on the wheel diameter.

The DCU provides the VCU with axle speed and the VCU calculates a true train speed. The true train speed is sent back to all DCUs and is further used for slip-and-slide control and wheel diameter calibration.

The motor speed and angle are always used in the torque control.

- **Slip and slide**

The slip-and-slide control makes maximum use of the available adhesion and uses the speed of both powered and non-powered axles to detect slip. In case of slipping, the torque reference is quickly reduced. The control is enabled in both driving and braking modes.

- **Overcurrent protection**

The DCU is equipped with protection from overcurrents in the phases. Phase overcurrents may occur during phase short circuits. The protection is based on the current measurements in two phases and the protective function is implemented in the computer hardware for quick overcurrent responses.

There is also short circuit detection and protection in the GDUs. The protection can handle both short circuits occurring before switching IGBT ON and short circuits occurring during the IGBT ON state. This protection is extremely fast and is activated both at short circuits in the power circuit and short circuits to earth.

The short circuit is detected on the IGBT collector-emitter supervision. When the protection is activated, the IGBT is switched OFF.

- **Earth fault detection**

During operation, the converter module is continually monitored for potential earth faults by the differential current sensor.

- **Cooling principle**

The internal fan circulates the internal air inside the converter box, distributing the heat evenly. As a result, the internal cooling system is a closed-loop system. Normally, the external fan starts as soon as the converter box is activated.

The internal fan starts as soon as the battery power supply is connected to the converter box.

The fan power can be disconnected manually during maintenance.

- **Diagnostics**

The DCU is equipped with extensive diagnostics and fault-tracing systems to minimize maintenance and downtime.

The system has a self-test function of the DCU and fault tracing/diagnostics of the components that can be performed during operation. There are also semi-automatic test functions to be used during maintenance.

To prevent damage to the equipment, some faults will result in the deactivation of the converter. Relevant information about the fault is being sent to the VCU.

By connecting a PC to the VCU, it is possible to download data from the internal transient recorder. The data from the recorder can be subject to extensive analysis by the maintenance crew.

- **Line trip**

If a serious fault is detected, for example, overvoltage, a protective shutdown is initiated to protect the converter box. The line trip relay on the DCU board is opened, which blocks the converter box, opens the separation contactor, and discharges the DC link capacitor.

3.2.7. Measuring sensors

- **Current sensors**

There are two current sensors in the motor converter, measuring one phase current each. The current through the third phase is continuously calculated in the DCU. The sum of the three-phase current is always zero.

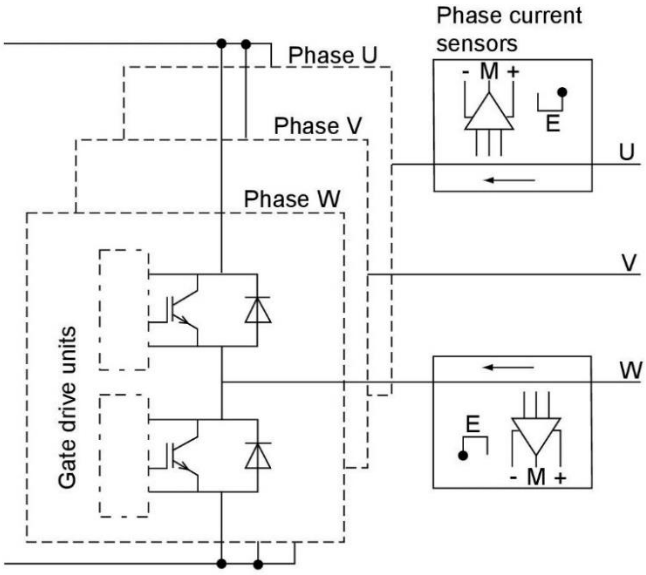


Figure 13. Phase current sensors in the MCM

All current measuring devices are powered with ±24 V DC from the DCU. The current signals are connected to the analog inputs on the computer.

High DC components in the phase currents will result in a deactivation of the converter box, to eliminate the torque ripple that will otherwise occur in the traction motors.

- **Voltage sensor**

The voltage sensor measures the voltage across the DC link capacitor. Information about the DC link voltage is continuously sent to the DCU. The information is used in the converter control algorithm, as well as for triggering protective actions.

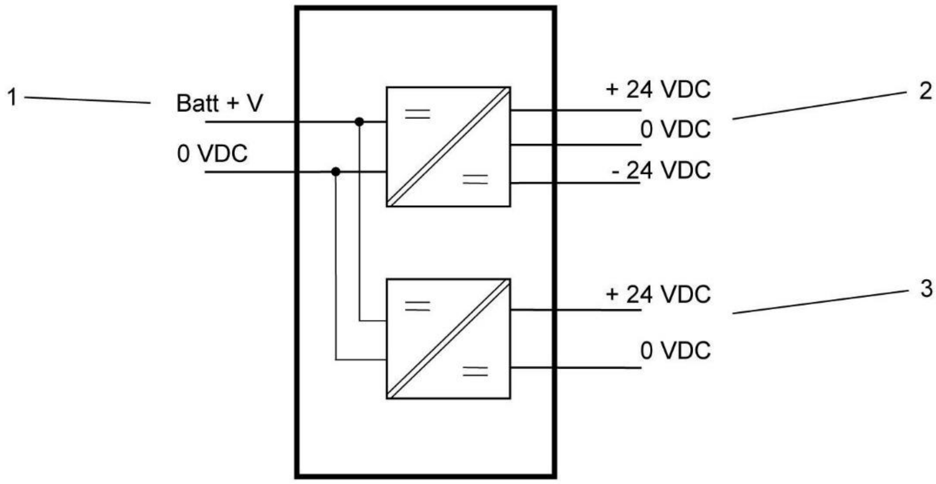
- **Temperature sensors**

There are two temperature sensors in the converter module, placed in the heat sink area (measuring heat sink temperature) and inside the module (measuring air temperature). They measure the temperature and send a signal to the DCU when they reach a predefined value.

When a certain (higher than normal) temperature is reached, the output power of the converter is limited. If the temperature remains high for a predefined time, a fault is indicated and the converter is deactivated. It will be activated again when the temperature drops.

3.2.8. Low voltage power supply

The input voltage is converted into the mentioned output voltages using a DC/DC converter (part of the PSU) with galvanically separated inputs and outputs. The battery voltage is also used to drive the external contactors.



1	Input battery voltage	2	Power to the DCU and measuring devices
3	Power to the GDUs		

Figure 14. Low voltage power supply

3.3. Product design

3.3.1. Converter module

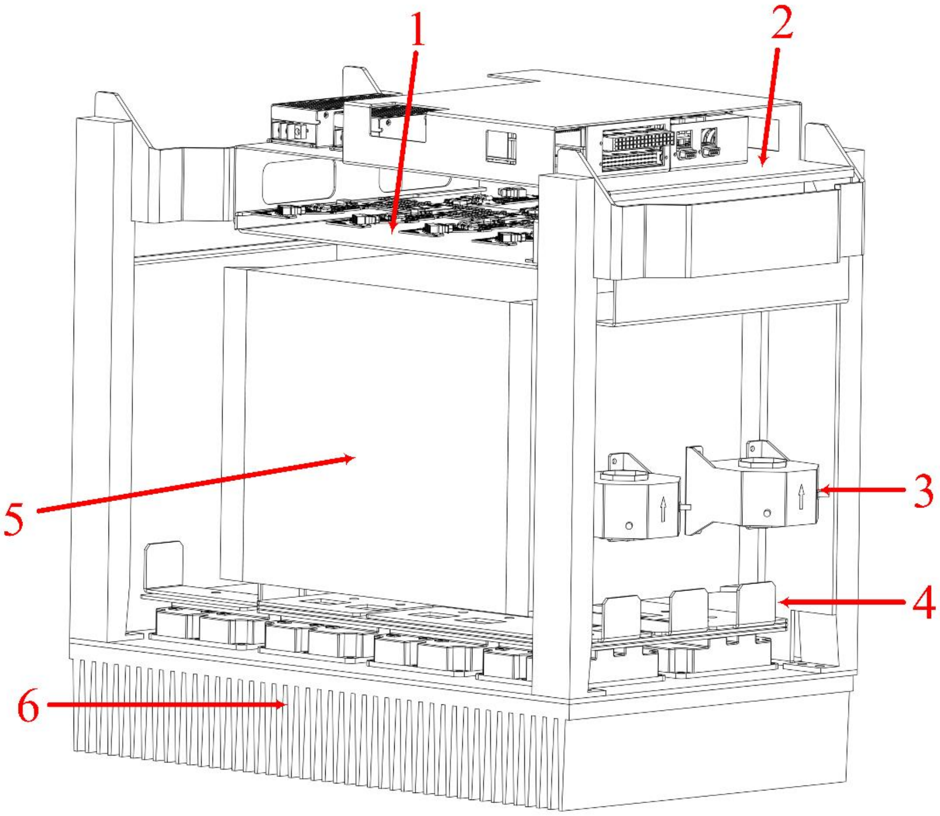
The converter module is air-cooled and based on IGBT technology. The module is assembled in a converter box, which is located in the undercarriage of the vehicle. The control signals are connected to the module with plug-in connectors. The drive control unit is assembled on top of the module.

The converter module contains the following sub-assemblies:

- DCU assembly
- GDU assembly
- DC terminal assembly
- DC link capacitor

- Power section
- AC (three-phase) terminal assembly

3.3.2. External view



1	GDU assembly	2	DCU assembly
3	Current sensors, three-phase terminal assembly	4	Power section
5	DC link capacitor	6	Heat sink

Figure 15. Motor converter module

3.3.3. DCU assembly

□ **Drive control unit (DCU) assembly**

The DCU assembly is located on top of the module and is partly screened to prevent electromagnetic interference between the power circuit and the DCU. The assembly has a non-enclosed design to facilitate cooling.

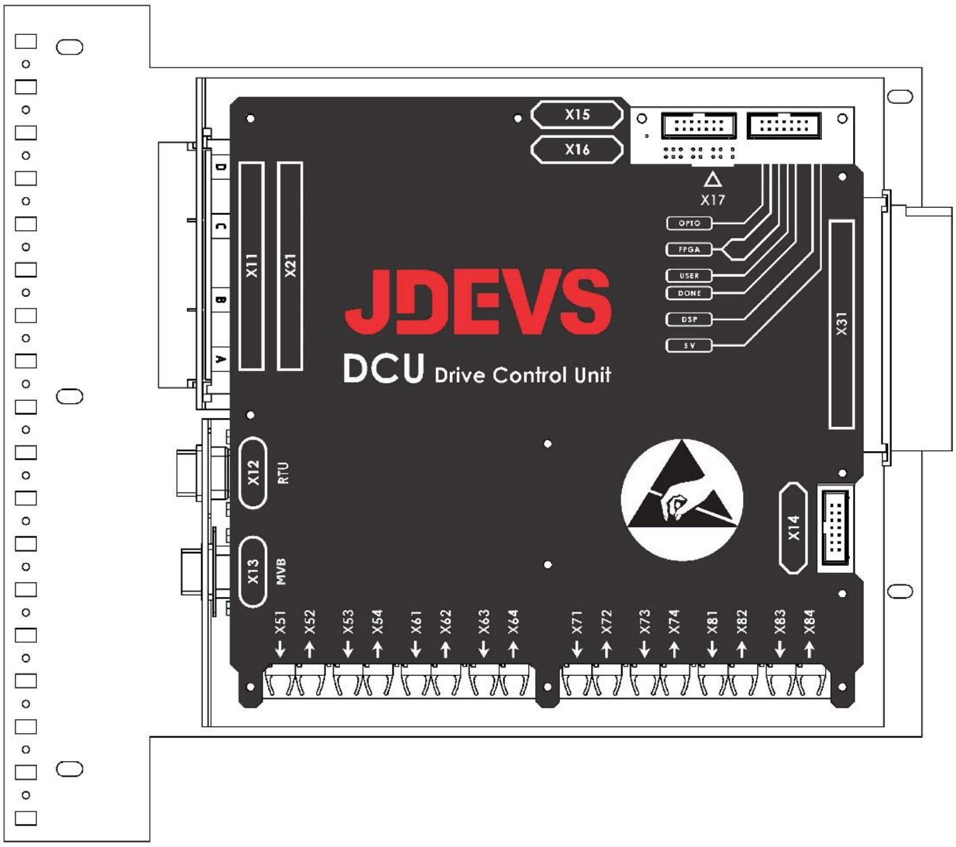


Figure 16. Drive control unit

□ **Drive control unit (DCU)**

The DCU is a part of the DCU assembly. It is designed to slide into a connection box and is easily accessible, being fixed on the top of the converter module.

The software in the DCU consists of an operating system and application software. The DCU hardware consists of several printed circuit boards:

- A base board
- An analogue input board
- A power supply board

All optical transmitters and receivers are located on the base board. The DCU is assembled on a metallic base plate, providing both stability and multiple earthing points.

There are separate interfaces for the MVB and DCU test connections.

□ **Power supply unit (PSU)**

The PSU consists of a DC-DC converter.

3.3.4. GDU assembly

□ **Gate drive unit (GDU) assembly**

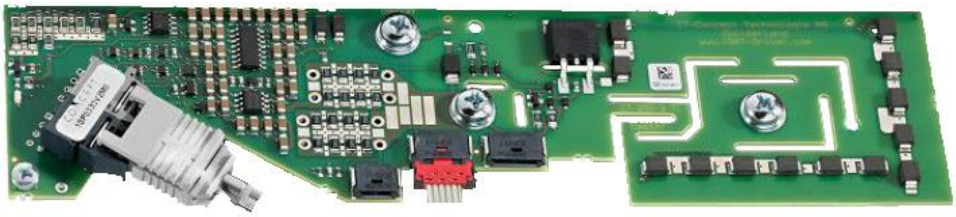


Figure 17. GDU assembly

□ **Gate drive unit (GDU)**

The gate drive units together with voltage transformer is assembled on a mounting plate, forming the GDU assembly.

□ **Voltage sensors**

The voltage sensor is assembled in a shielding box on the apparatus plate. The sensor measures the DC link voltage on the DC-plus and DC-minus terminals and AC voltage between AC lines.

3.3.5. Sensors

□ **Temperature sensor**

In the module there are two temperature sensors:

- One on the GDU assembly, measuring the internal air.
- One on the power section, measuring the heat sink temperature.

□ **Current sensor**

The (differential) current sensors measure the difference between the incoming DC+ current and the outgoing DC+ current. The sensors are provided with a test coil that could be periodically energized to ensure the sensor is working properly.

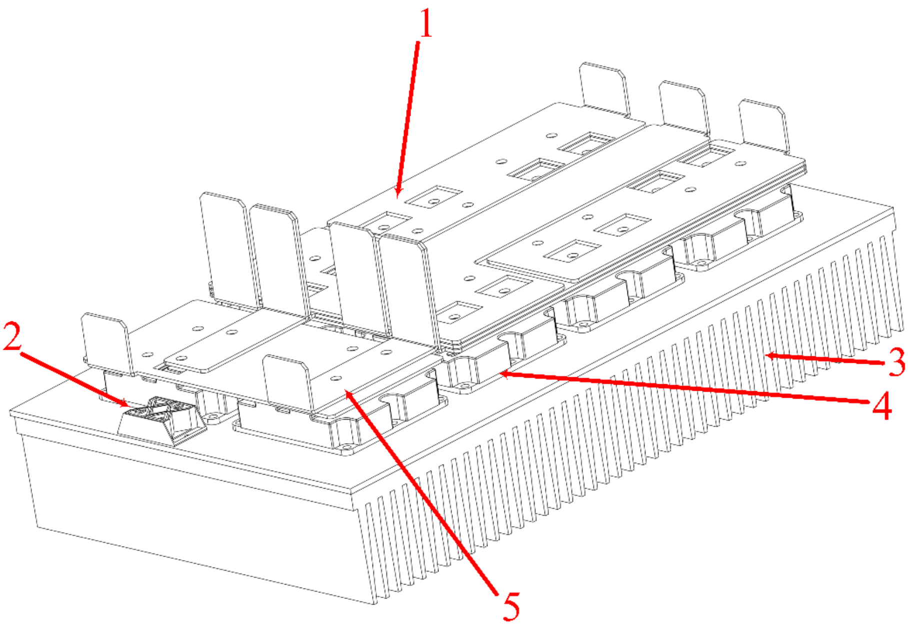
□ **Phase current sensor**

The phase current sensor detects an electrical current on a busbar and generates a signal that is proportional to the current.

3.3.6. Power section

- **Power section**

The figure below shows the power section.



1	Three-phase laminated busbar	2	Discharge resistor
3	Heat sink	4	IGBT module (7 pcs)
5	DC laminated busbar		

Figure 18. Power section

- **IGBT modules**

The IGBT modules are mounted with screws directly to the heat sink for optimal cooling. Cooling of the IGBTs is a very important factor in their performance.

Figure 19. IGBT module

- **OVP resistors**

The two OVP resistors are mounted with screws on the heat sink.

- **Discharging resistor**

The discharging resistor is assembled with screws directly to the heat sink. The resistor is dimensioned to be able to discharge the DC link capacitor to less than 50V within 5 minutes, if the capacitor has not been discharged actively.

3.3.7. DC link capacitor

The DC link capacitor consists of two capacitors connected in parallel, housed in the same enclosure.

The capacitor is of the self-healing type with segmented metallization using metallized polypropylene. The capacitor is dry (contains no electrolyte or oil) and is gas insulated (gas pressure 1 bar).

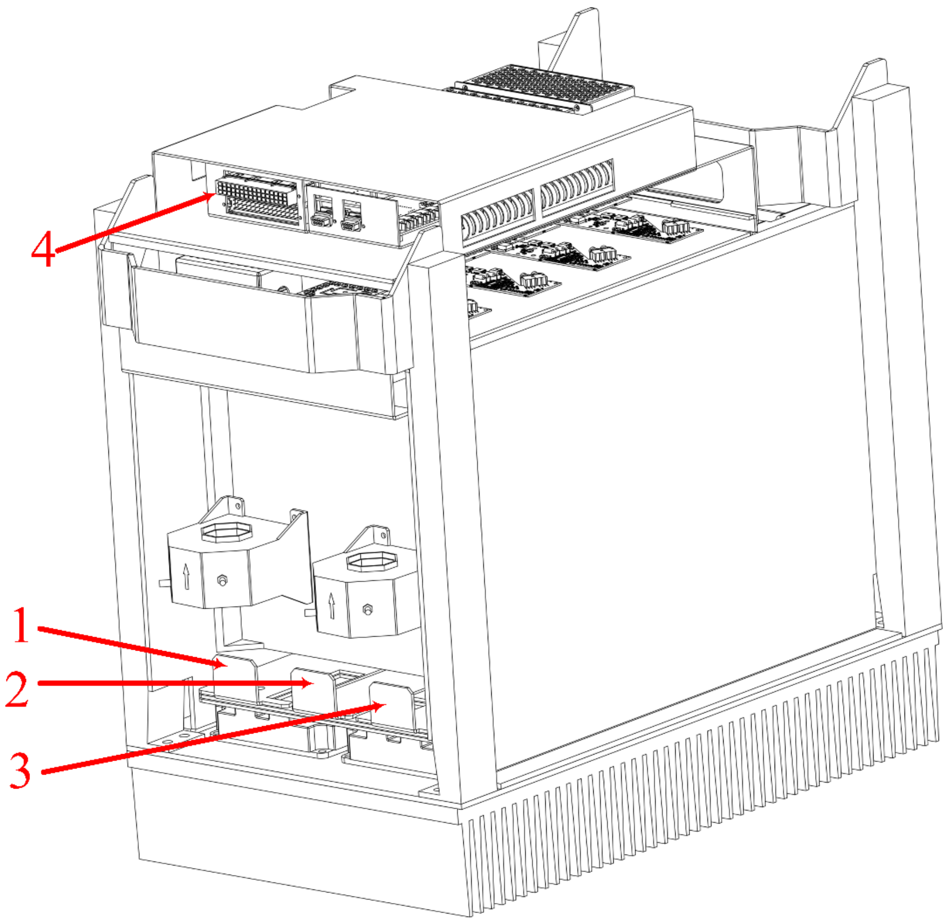
3.3.8. Signal interface

- **Internal connections and busbars**

All communications between the DCU and the GDUs are made using optical cables. The optical cables galvanically separate the circuit boards and isolate the battery voltage from the power circuit.

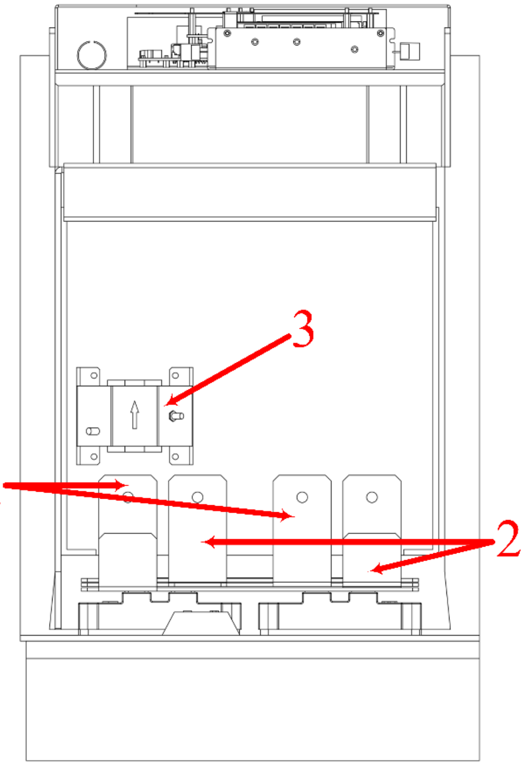
Laminated, low inductive, busbars are used between the DC link capacitors and the converter phases (IGBT modules). This minimizes the inductance, which in turn minimizes the voltage overshoots and switching losses.

Connections to equipment outside the converter module are made by copper busbars. These connections are the three-phase motor connections, the chopper, and the DC-plus and DC-minus connections.



1	Busbar, phase U	2	Busbar, phase V
3	Busbar, phase W	4	Control signals

Figure 20. Phase connections for MCM.



1	DC +	2	DC -
3	Current sensor for DC side	4	Connection box, control signals

Figure 21. Power connections for MCM.

3.4. Technical specification

3.4.1. Electrical data

Table 2. Electrical data of MCM

Converter module	Value
Input nominal voltage	1500 V DC
Input max. voltage continuous	2000 V DC
Input min. voltage continuous	1000 V DC
Three-phase output voltage	400 V AC
Output frequency	50 Hz
Output phase current, max. continuously, fundamental frequency	400 A RMS
Trip level	2000 V DC

3.4.2. DC link capacitor

The body of the capacitor is non-magnetic stainless steel. It has a capacitance of 2 mF, a rated DC voltage of 2100 V, and a rated current of 120 A.

3.4.3. Power supply unit, voltage range

The power supply units provide regulated supply voltage to the DCUs and GDUs. The units are specified for a nominal 24V DC to account for the 110 V DC battery voltage available on the train.

3.4.4. IGBT module, phases

Table 3. Specification of IGBT module

Type of value	Value
V_{CEM}	Upper than 3300 V
I_{NOM}	400 A