teknoCEA

170 kVA, 800 VDC Three phase voltage source converter

PCO-170T800 Technical Reference

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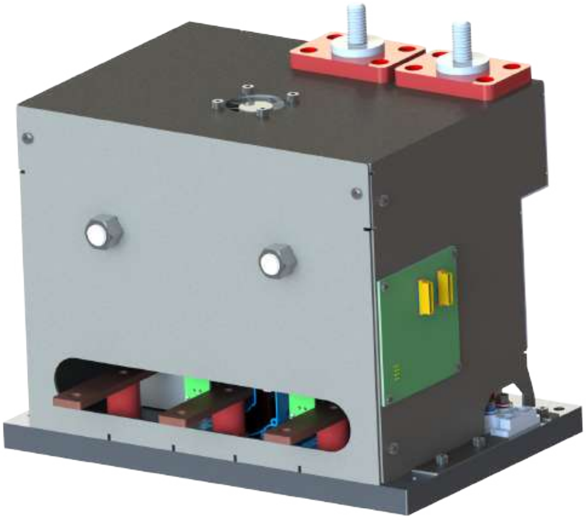

2024 **COMPONENTS**

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About This Manual

This document serves both as a datasheet and as a user manual for the PCO-170T800. This power converter stack is based on three half-bridge IGBT modules from Semikron connected as a three-phase voltage source inverter, and is able to output 170 kVA at an output voltage of 400 V_{RMS}.

Even though the power converter is a three-phase voltage source inverter, other topologies can also be implemented on the basis of the three half bridges it incorporates (AC to DC active rectifier, active filters, DC to DC converter, interleaved converters, . . .). In addition, this module incorporates sensors for the measurement of 2 output currents, the DC Bus voltage level and the cold plate's temperature.

Information About Cautions

This book may contain cautions.

> IMPORTANT NOTICE
> **This is an example of a caution**

A caution statement describes a situation that could potentially damage your hardware, or other equipment. The information in a caution is provided for your protection. Please read each caution carefully.

Related Documents

Semikron SKM600GB12T4 Datasheet
teknoCEA CDA01-CU5 Technical Reference

1 Introduction to PCO-170T800

The PCO-170T800 is a versatile power electronics platform that allows designers to implement the most used power converter topologies in a digital control environment. It includes all the necessary hardware elements to implement a grid connected inverter with up to 170 kVA, power rating achieved at 400 V_{RMS} and 250 A_{RMS}.

The power converter is a three-phase voltage source inverter, but other topologies can be implemented on the basis of the three half bridges it incorporates (AC to DC active rectifier, active filters, DC to DC converter, interleaved converters, ...). The Semikron semiconductors at the core of this stack are packed in a reliable and compact module that can be controlled uniquely and for safety purposes an NTC is incorporated on the cooling plate so as to measure the temperature of the semiconductors.

Regarding the measurement of the variables in the Stack, both DC bus voltage and two out of the three current outputs are measured, thus allowing for a high flexibility in implementing different converter topologies and control structures. Beyond that, all voltage and current measurements include galvanic isolation.

As for the three drivers controlling the IGBT modules, the DRV-2D6W, these are isolated and include undervoltage protection, overcurrent protection and soft turn-off in case of an overcurrent trip, when the transistors are forced to open.

The connection to the control system is done by a flat cable connector on the PCB mounted at the side of the converter casing. More specifically, this connector (J2) is used for both sending and receiving signals to and from the Controller Board, including the 24V and ± 15V power supplies, the PWM signals or the measurements from the probes.

In addition, a discharge circuit for the DC bus capacitors is implemented with a 10kΩ resistor mounted on the same cooling plate as the IGBT modules.

In Figure 1 a rendered image of the stack is shown.

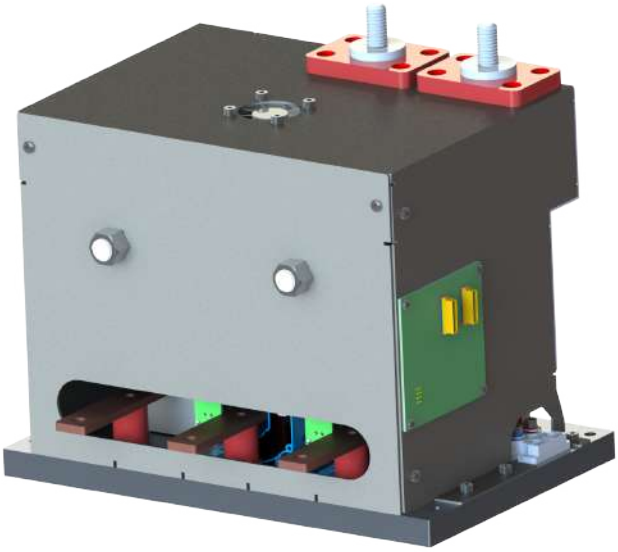

Figure 1: Rendered image of the Stack

The following figure, Figure 2, shows the block diagram of the PCO-170T800, where its main elements and connections in relation to the connector with which the user interacts (the already mentioned J2) can be observed.

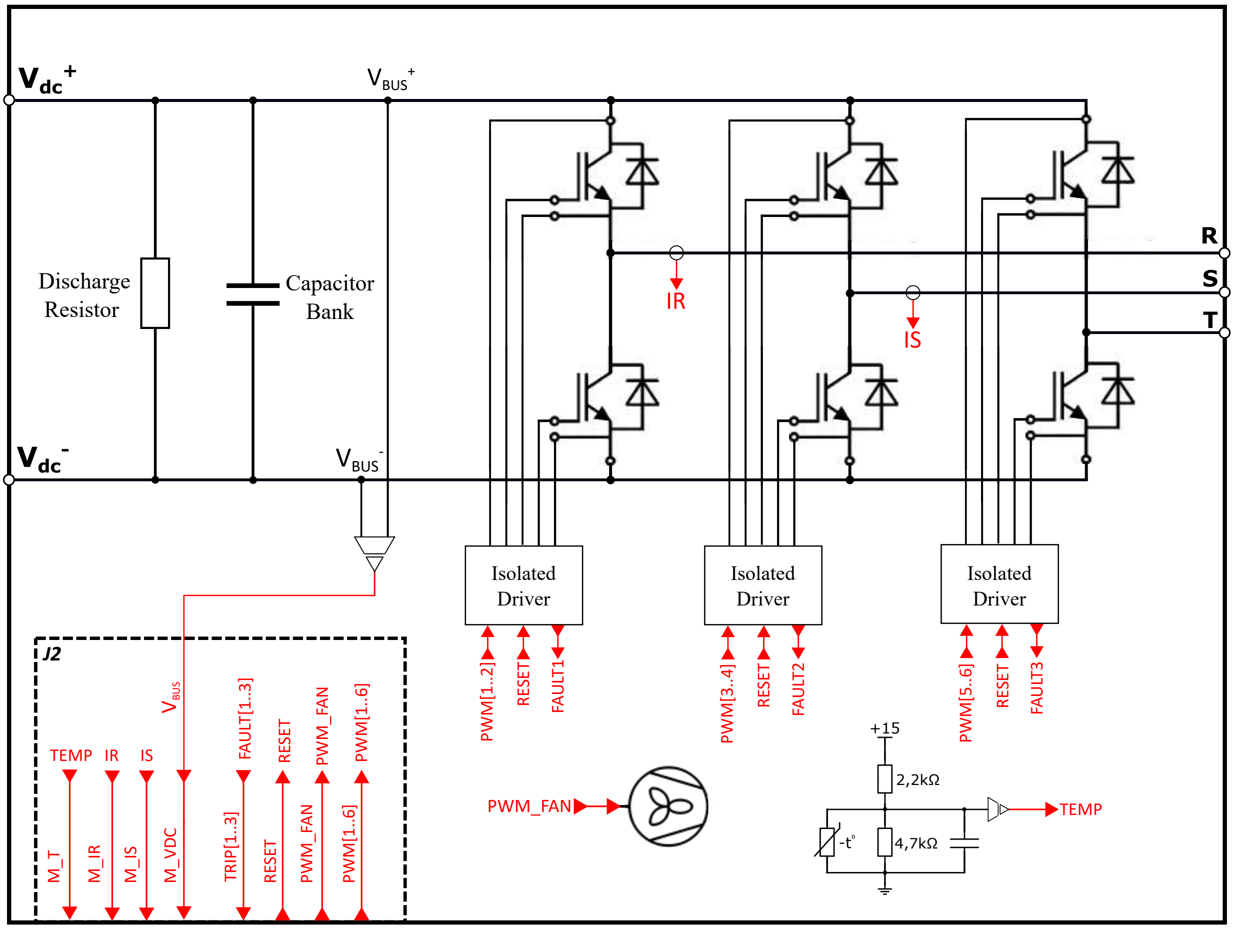

Figure 2: Block diagram of the PCO-170T800 converter.

2 Electrical characteristics

Symbol	Description	Min.	Typ.	Max.	Unit
Main Parameters					
V_{ac}	Output rated voltage (50 Hz)		400		V_{rms}
I_{out}	Output rated current (50 Hz) @ $T_a = 40^{\circ}C$		250		A_{rms}
S_{out}	Output power @ $T_a = 40^{\circ}C$		170		kVA_{rms}
V_{dc}	DC bus voltage			800	V
f_s	Switching frequency		4	8	kHz
T_a	Coldplate temperature		40	60	°C
Digital inputs					
V_{xi_H}	High-level signal	3,50		5,00	V
V_{xi_L}	Low-level signal	0,00		1,50	V
Digital outputs					
V_{xo_H}	High-level signal @ $I_{oH} = -32mA$		Open Collector		V
V_{xo_L}	Low-level signal @ $I_{oH} = 32mA$			0,2	V
Measurements					
DC Voltage sensor	Input voltage measurement range	0		1000	V
	Output voltage measurement range	0,00		10,00	V
	Gain		0,01		V/V
	Accuracy		±5		%
	Bandwidth		100		kHz
Current sensor	Primary current		300		A_{rms}
	Primary current range		± 500		A
	Secondary current		150		mA_{rms}
	Gain		1 : 2000		A/A
	Accuracy		$\pm 0,5$		%
T+	Semiconductor minimum recommended operating temperature output voltage (-40°C)		10,14		V
	Semiconductor casing maximum temperature output voltage (125°C)		0,55		V
Power supply					
V_s	24 V power supply voltage	22	24	26	V
ΔV_s	24 V power supply ripple		200		mV
I_s	24 V power supply current			1	A
V_{s19}	+15 V output power supply voltage	14	15	16	V
V_{s20}	-15 V output power supply voltage	-16	-15	-14	V
$I_{s19,20}$	±15 V power supply current			380	mA

Table 1: PCO-170T800 electrical characteristics.

3 General Description

3.1 System components

Preceding the description of the individual components of the PCO-170T800 and their function, the figure below, figure 3, displays a rendered image of the power converter stack, in which its main components are identified:

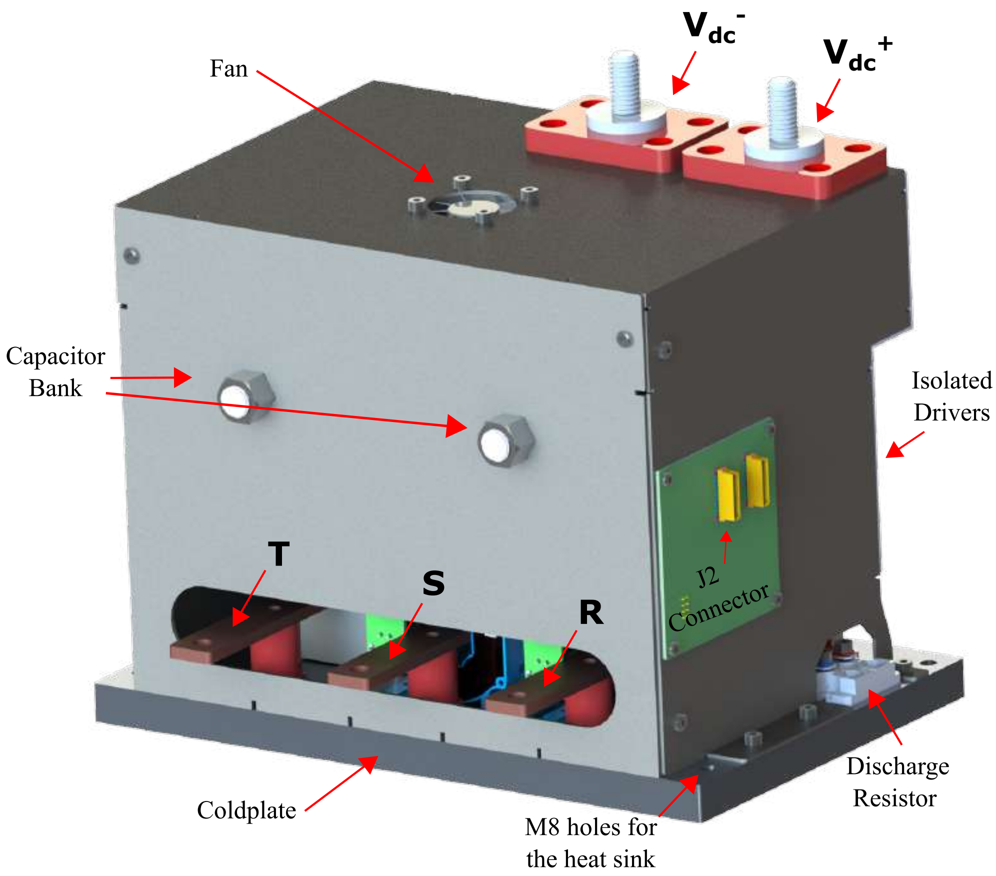

Figure 3: Rendered image of the Stack

3.1.1 IGBT modules

The PCO-170T800 power converter consists of three half-bridge IGBT modules connected as a three-phase voltage source inverter, as seen in Figure 2, with each half bridge generating an output phase voltage controlled by the switching signals of the transistors (PWM signals), these being the main signals sent to the drivers by the controller board. Additionally, in subsection 3.2 these connections are shown in detail.

The IGBT modules used in the PCO-170T800 are the SKM600GB12T4 modules by SEMIKRON, the circuit of which is shown in the following figure. For further information regarding the modules reading the SEMIKRON datasheet is utterly recommended.

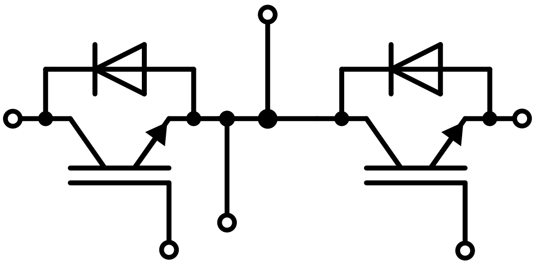

Figure 4: Circuit diagram of the IGBT modules

As stated in their datasheet, for safety requirements, the temperature at the semiconductors should not be higher than 150 °C, with the maximum temperature at the outer casing being 125 °C, otherwise there is a risk that the semiconductors could be irreparably damaged. For this particular reason, it is highly recommended that the temperature measured by the thermistor does not exceed 100 °C. This value is merely a suggestion for the most common operating conditions, which is why, it is especially relevant to realize a thermal study of the converter for each particular application in order to prevent damages.

IMPORTANT NOTICE
The PCO-170T800 does not include any protection against over temperature of the semiconductors. This protection must be implemented by the user through the control system.

3.1.2 Driver Circuit

The three made-in-house drivers found in the stack, the DRV-2D6W, are optically isolated, and as it has been previously mentioned, each IGBT module in the stack has its own driver, thus allowing for an independent control of each transistor. Nonetheless, no cross conduction protection or dead-time insertion in complementary PWM signals is implemented in the PCO-170T800, since these features must be implemented in the control system by the user. Figure 5 shows the pin configuration of the gate driver IC, in which the pins that this subsection will focus on can be observed, FAULT, RESET, and IN+, where the PWM signal reaches the IC.

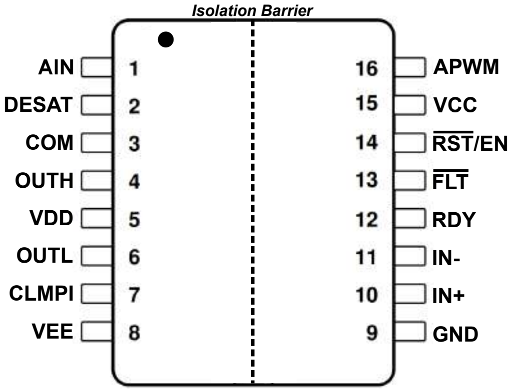

Figure 5: UCC21759-Q1 Gate Driver Pin Configuration

The DRV-2D6W is a state-of-the-art driver based on the UCC21759-Q1 by Texas Instruments with many protection features, mainly the under-voltage lock-out (UVLO), which protects the driver from an isolated power supply failure. This system, in case of a failure, is in charge of stopping the switching of the transistors and sending an error signal to the control system.

Moreover, the DESAT function, an additional safeguarding feature, prevents the desaturation of the IGBT modules, therefore protecting them from overcurrents. This function works by having the DESAT pin monitor the IGBT's V_{ce} voltage. When the DESAT fault is detected, the soft turn-off is triggered, in the meantime minimizing the short circuit energy while reducing the overshoot voltage on the switches. This soft turn-off mechanism prevents the destruction of the IGBT from large induced voltages.

The DESAT fault detection circuitry must remain disabled for a short time period following the turn-on of the IGBT to allow the collector voltage to fall below the DESAT threshold. The DESAT blanking time is calculated in terms of external capacitance, FAULT threshold voltage and DESAT charge current, resulting in a leading edge blanking time of 200 ns.

All these failure modes (UVLO and DESAT) generate a unique fault signal for each driver back to the control system. The fault output in each driver is open-collector and the top and bottom signals are connected in parallel so as to generate a unique open-drain fault signal for each converter leg, available in the digital section of connector J2.

The FAULT signal is latched persistently after a fault situation, in order to restore the operation of the driver the RESET signal can be used by the control system. Regarding this signal, in proximity to the IC a pull-down resistor is placed, resulting in a digital signal which must be set to high by the control system to operate the drivers and must be set to low to reset the driver fault.

Last but certainly not least, the IN+ pin of the integrated circuit refers to a non-inverting gate driver control input, from where the PWM signal sent by the user reaches the driver circuit. This pin, exactly like RESET and FAULT, has a voltage range from -0,3 to 5 V, being the latter the voltage supplied to the IC.

IMPORTANT NOTICE
The only safety features the drivers incorporate are the ones implemented in the driver chip. No additional protection has been implemented in the PCO-170T800, thus it is strongly advisable to add some sort of protection routine in the control system in the instance that a Fault_Drivers event occurred.
As it has been stated, no cross conduction protection or dead-time insertion in complementary PWM signals has been implemented in the PCO-170T800, hence, these features must be implemented in the control system by the user.

3.1.3 DC bus capacitor bank

The DC bus is formed by the parallel connection of two 1000 μF/900 V metallized polypropylene film capacitors, thus being the total capacitance around 2000μF. In addition, 3 additional snubber capacitors are placed close to the modules and, as seen in figure 3, a 10 kΩ discharge resistor is mounted onto the cold plate as well.

Owing to the presence of a discharge resistor inside the stack, the PCO-170T800 enables the user to carry out a controlled discharge of the DC bus capacitors, and given the resistance of the resistor and the capacitors being used, it takes 60 s to discharge the DC bus capacitors from 800 V DC to 40 V DC, a non-dangerous voltage level. Additionally, through the use of an external discharge circuit with contactors or similarly-functioning components, this time can be reduced. Moreover, the placement of this resistor ensures that in the event of a loss of power, the capacitors will be automatically discharged to a safe voltage level.

IMPORTANT NOTICE
The pre-charge of the DC bus must be implemented by an external pre-charge circuit and monitored by the user's control system. Additionally, it is strongly recommended to implement a control algorithm verifying the pre-charge process not to damage the converter.

IMPORTANT NOTICE
The PCO-170T800 does not implement any protection function in case of overvoltage at the DC bus capacitors. These features must be implemented in the control system by the user.

3.1.4 Voltage sensing

One of the many features the PCO-170T800 includes is the measurement of the DC bus voltage. This functionality is supplied by three of the pins in J2, since it requires a voltage supply level of ±15 V and a connection to GND. Finally, the measurement is available at M_VDC, another one of the analog pins in J2 (Table 3).

The signal that reaches the connector has been adapted by the stack's circuitry by implementing a gain of 1/100, since the sensor's range is 1000V and the unipolar signal at the output, that has also been filtered, ranges from 0 to 10 V.

This aforementioned adaptation of the DC bus voltage measurement consists of different stages and an amplifier chip at its core, the ACPL-C79B, a device that has a bandwidth of 200 kHz. The first stage includes a first order filter with a cut-off frequency of 167 kHz and, right after the amplifier, the third stage acts as a second order filter with a cut-off frequency of 123 kHz. All in all, the overall DC bus voltage measurement filter's cutoff frequency is 100 kHz.

IMPORTANT NOTICE
The voltage at the input of the external voltage measurements shall not exceed 800 V. Exceeding the maximum voltage may cause damages to the converter.

3.1.5 Current sensing

Given the symmetrical nature of a three-phase system, the measurement of only two phases provides sufficient information for most applications, which is the reason just currents R and S are measured. These current measurements are done by closed-loop hall-effect sensors from LEM, more specifically the LF 305-S/SP10. With a range of ±500 A and a gain of 1/2000, since that is the ratio of turns between the primary and secondary windings.

The transducers are supplied using the +15V and -15V pins in J2 and the signals produced in the secondary winding, I_R and I_S, are sent to the control board using the same connector. For proper measurement, the user ought to implement a shunt resistor to these signals, with the objective of converting these currents into a voltage within a desired range. According to the manufacturer, these shunt resistors must have a resistance of up to 21 Ω should the ambient temperature be 70°C in order to prevent the saturation of the sensor's output stage (for further information, refer to the transducer's datasheet).

For instance, if it were the case that one wanted to have a bipolar voltage signal going from -5V to 5V, since the measuring range is ±500 A, a 20Ω shunt resistor must be implemented, as shown in the calculations below:

$$\begin{cases} 500\,A \cdot \dfrac{1}{2000} = 0,25\,A \\ \dfrac{5\,V}{0,25\,A} = 20\,\Omega \end{cases} \tag{1}$$

3.1.6 Temperature measurement

With regard to the aforementioned temperature measurement, the stack includes a NTC sensor to measure the cold plates' temperature, which is placed on the cold plate, at the halfway point between the IGBT modules, the output of which is also measured. Specifically, the thermistor used is the 5k 3988 1% manufactured by TDK Epcos and the resistance's dependence with the sensor's temperature can be computed as follows:

$$R(T) = R_0 \cdot e^{\left(B \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)\right)} \tag{2}$$

Where $B = 3988\ ^{\circ}C^{-1}$, $R_0 = 5\mathrm{k}\Omega$ and $T_0 = 298{,}15$ K.

The PCO-170T800, includes an adaptation stage to adjust the voltage outputted at the J2 connector (as seen in Figure 2, where the temperature measurement is available at J2) so that at -30 °C the voltage is 10,07 V and at 140 °C 0,76 V. The following figure serves as an approximation of the circuit, with the two resistors working with the thermistor as a resistive divider and a capacitor for noise-filtering.

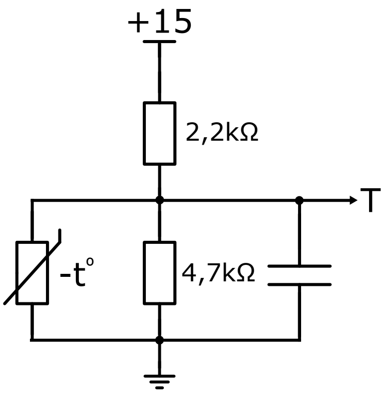

Figure 6: NTC signal's resistive divider

With this divider in consideration, the following graph illustrating the relation between the thermistor's temperature and the voltage is obtained:

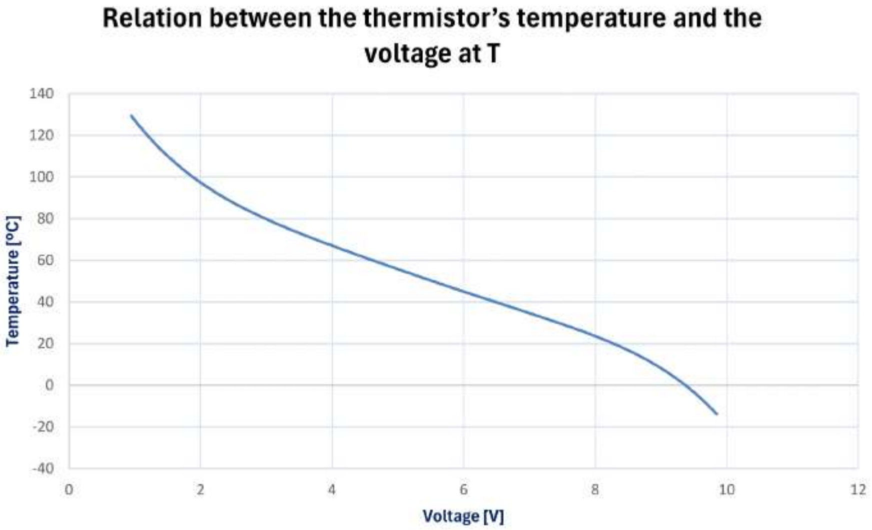

Figure 7: Relation between the thermistor's temperature and the voltage at T

And finally, from Figure 7 a polynomial equation is obtained, from which one is able to implement the NTC's temperature readings into the code:

$$T(V) = 0,0139V^5 + 0,3799V^4 - 4,1382V^3 + 22,724V^2 - 74,314V + 182,56 \tag{3}$$

As an example, for a 100 °C temperature at the thermistor, the resistance will be 339,11 Ω and the voltage at the measuring point (T) will be 1,885 V.

Still, it is important to state how the temperature of the thermistor is in fact not the temperature of the semiconductors, it will be similar to the temperature of the ceramic plate of the semiconductors' module, thus it is used as a reasonable approximation of the temperature on the surface of the heat sink.

Last but not least, it is advisable to implement a low-pass filter in the ADC adaptation circuitry in order to filter the commutation noise, being the cut-off frequency at least 10 times lower than the switching frequency.

3.1.7 Cooling system

It is strictly necessary that a heat sink is to be mounted directly under the stack's cooling plate so as to further assist with heat dissipation, always making sure to apply a coat of thermal paste in between the two pieces of hardware. This heat sink can be both air-cooled or water-cooled, and below three graphs showing the relation between dissipated heat and output power necessary for the required calculations are provided.

These figures show three trendlines each, which, as can be observed in their corresponding legends, refer to three different DC bus voltages. Additionally, the figures have been calculated under the following conditions:

$$T_{Coldplate} = 80^{\circ}C;\ f_{out} = 50\text{ Hz};\ V_{out} = 400\ V_{rms};\ \text{Modulation technique: SVPWM};\ \cos(\phi) = 1$$

Figure 8: Losses vs. output power at a switching frequency of 8 kHz

Figure 9: Losses vs. output power at a switching frequency of 6 kHz

Figure 10: Losses vs. output power at a switching frequency of 4 kHz

Additionally, the following figure shows the relation between output power and the maximum temperature that the coldplate should reach so as not to irreversibly damage the converter's components. Furthermore, multiple trendlines are shown, one for each different switching frequency, and as a note, all calculations were made under all the same conditions as before except for the coldplate's temperature:

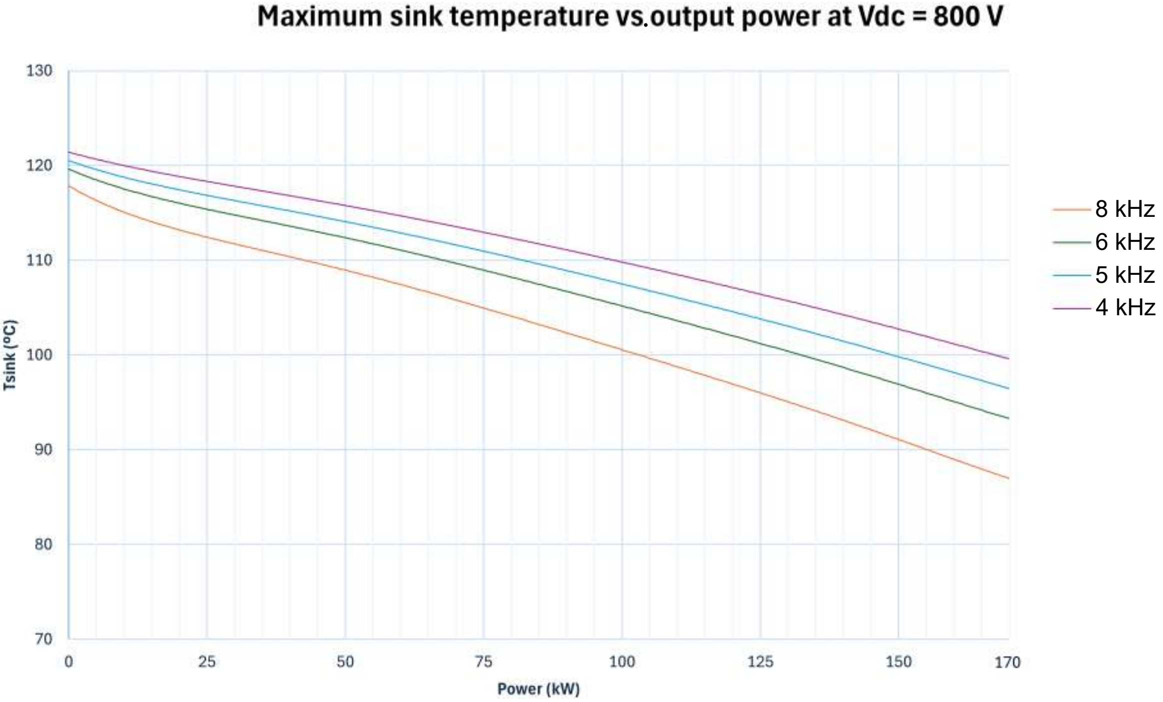

Figure 11: Maximum sink temperature vs. output power at Vdc = 800 V

Aside from that, the cooling system also includes a 24 V fan at the top, which can be controlled by the user using the Fan signal (PWN_FAN in Figure 2) and consumes 85 mA. This arrangement is put together with the purpose of injecting cold air into the stack, so that the interior of the PCO-170T800 is pressurized and dust shall have a much harder time finding its way into the converter.

IMPORTANT NOTICE
The PCO-170T800 does not include any protection against over temperature of the semiconductors. This protection must be implemented by the user in the control system.
The user is responsible for starting or stopping the cooling system in order to control the semiconductors' temperature.

3.2 Connectors

In this subsection, a breakdown of all the pins in the J2 connector, the one with which the user is able to interact with the converter, will be provided.

This connector is a 26 pin IDC connector by Harting, reference number 15120262601000, therefore a recommended female connector is another one from Harting, reference number 15290262502000. Down below, an image of the former is shown.

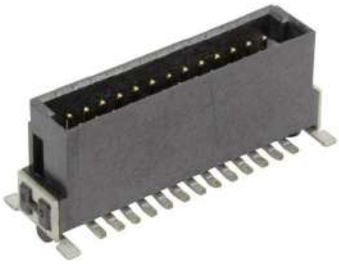

Figure 12: 26 pin IDC connector found in the PCO-170T800 [Harting]

3.2.1 J2 connector, Digital Signals

The J2 connector has a 13×2 pin arrangement and, as has been repeatedly expressed throughout the document, it is the connector with which the user is able to communicate with the PCO-170T800. Rather than having two different connectors, one for all the analog signals and a second for the digital ones, the stack's J2 connector incorporates both kinds of electrical signals, just as it can be seen in Figure 13, which shows the connector's schematics, which include the digital signals displayed in red and the analog ones shown in blue.

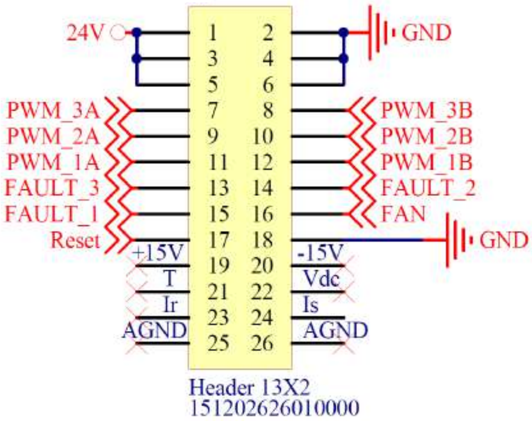

Figure 13: Schematics of the J2 connector

Pin arrangement and function of the digital signals of the J2 connector is summarized in Table 2.

Pin	Pin name	Function	Description
1	+24 V	Power	Power supply +24 V_{DC}
2	GND	Power	Ground for power supply
3	+24 V	Power	Power supply +24 V_{DC}
4	GND	Power	Ground for power supply
5	+24 V	Power	Power supply +24 V_{DC}
6	GND	Power	Ground for power supply
7	PWM_3A	Digital input	PWM TH signal
8	PWM_3B	Digital input	PWM TL signal
9	PWM_2A	Digital input	PWM SH signal
10	PWM_2B	Digital input	PWM SL signal
11	PWM_1A	Digital input	PWM RH signal
12	PWM_1B	Digital input	PWM RL signal
13	FAULT_3	Digital output	Driver error. Active low
14	FAULT_2	Digital output	Driver error. Active low
15	FAULT_1	Digital output	Driver error. Active low
16	FAN	Digital input	Fan control
17	Reset	Digital input	Driver reset. Active low
18	GND	Power	Ground for power supply

Table 2: J2 connector, digital pins, pin function and arrangement

In subsection 3.2.3, more information about the requirements the signals must meet will be presented.

3.2.2 J2 connector, Analog signals

The analog pins in J2 are the pins 19 to 26, 8 pins tasked with both supplying the sensors in the system and ensuring that those measurements are available for the user.

Pin arrangement and function of the analog signals of the J2 connector is summarized in Table 3.

Pin	Pin name	Function	Description
19	+15 V	Power	Power supply +15 V_{DC}
20	-15 V	Power	Power supply -15 V_{DC}
21	T	Analog output	Semiconductor module temperature
22	Vdc	Power	DC bus voltage
23	Ir	Analog output	R phase current
24	Is	Analog output	S phase current
25	AGND	Power	Analog Ground
26	AGND	Power	Analog Ground

Table 3: J2 connector, analog pins, pin function and arrangement

Just as in subsection 3.2.1, a more in-depth description of the characteristics that these signals must adhere to is provided in the following subsection.

3.2.3 J2 connector, Electrical characteristics

The following table shows in more detail the requirements the signals previously presented must meet:

Symbol	Description	Min.	Typ.	Max.	Unit
Power supplies					
V_s	24 V power supply voltage	22	24	26	V
ΔV_s	24 V power supply ripple		200		mV
I_s	24 V power supply current			1	A
V_{s19}	+15 V output power supply voltage	14	15	16	V
V_{s20}	-15 V output power supply voltage	-16	-15	-14	V
$I_{s19,20}$	±15 V power supply current			380	mA
Digital Signals					
PWM_X	Digital PWM signals	-0,3		5	V
$FAULT$	Driver error. Active low	-0,3		5	V
$Reset$	Driver reset. Active low	-0,3		5	V
FAN	Fan control signal	-0.3		5	V
Analog Signals					
I_r	R phase current measurement	-0,25		0,25	A
I_s	S phase current measurement	-0,25		0,25	A
V_{dc}	DC bus voltage measurement	0		10	V
T	Semiconductor module temperature measurement	0,55		10	V

Table 4: J2 connector, electrical characteristics

4 Operation

4.1 Start-up

This subsection will cover an example of a start-up procedure of the PCO-170T800 working in unison with the CDA01-CU5 Control Board, yet another component from teknoCEA.

4.1.1 DC Pre-charge

In contrast to electrolytic capacitors, the ones found in the PCO-170T800 are metallized propylene capacitors, and thus, due to their stable dielectric properties over time, a reforming procedure is not required.

A pre-charge of the DC bus capacitors must be done prior to operation, however, the PCO-170T800 does not include a pre-charge system for the DC bus, therefore, it is essential to make use of an external DC pre-charge system.

Figure 14 shows a block diagram in which an example of the connection of a pre-charge circuit for a DC voltage source is shown.

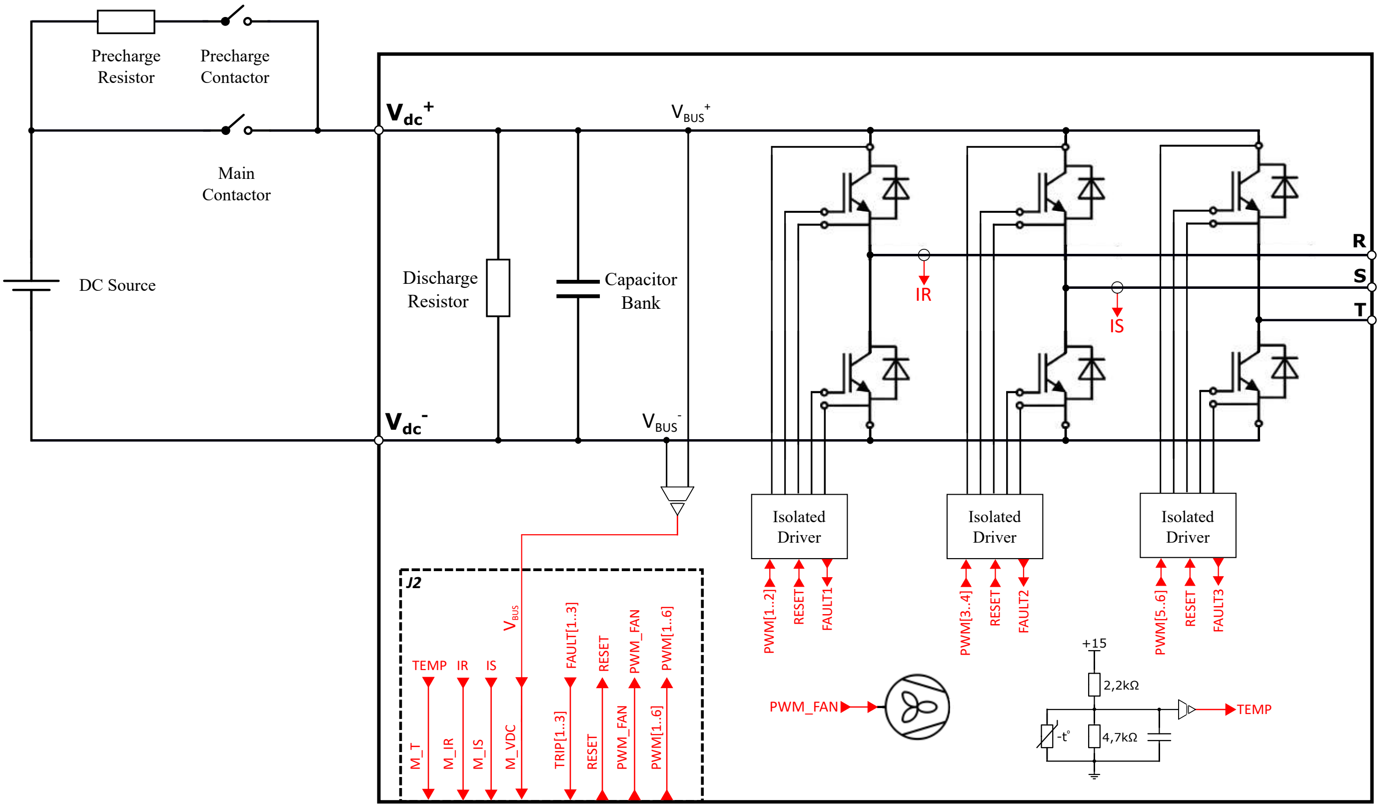

Figure 14: DC bus pre-charge connection example for a DC voltage source

The pre-charge procedure implemented by the user should be as follows:

1. Connect the PCO-170T800 to the Control Board through the J2 connector.
2. Supply the control system and therefore the PCO-170T800 and all the monitoring devices contained within it.
3. Ensure that the DC bus voltage is 0 V.
4. Close the relay to the precharge circuit until the precharge of the DC bus capacitors is completed.
5. Once the desired DC bus voltage level is reached, the main contactor should be closed.
6. After closing the DC source relay, the precharge relay can be opened.
7. The operation may be started.

Instead of a DC precharge circuit, the converter may be precharged from the AC (or output) side with an analogous circuit design. In this case, the DC link will be energized through the freewheeling diodes of the power semiconductor modules.

IMPORTANT NOTICE
Do not immediately apply full DC voltage or capacitors may explode

4.2 Security Precautions

4.2.1 General precautions

Do not disconnect any cable under load nor pull any cable, since it could cause their breaking or unplugging.

Before any intervention, the user must ensure that no high voltage is still present on the DC bus capacitors or other elements and shut down any power supply connected to the PCO-170T800. Likewise, under no circumstances should the converter be manipulated when in operation, and therefore, when high voltage can be measured at the DC bus capacitors.

The system in which the PCO-170T800 is to be incorporated should be up to safety standards, the placement of safety elements such as an emergency stop button, fuses, and a power indicator light is strongly advisable. In addition, all personnel working on the power converter must be qualified and in possession of all the specialized equipment required in this field of work, such as insulated hand tools and gloves, safety glasses and footwear as well as protective clothing.

4.2.2 Maintenance

It is highly recommended to clean the PCO-170T800 regularly in order to avoid short-circuits between phases or in the DC bus, effectively removing all dust and dirt that will have collected on the stack's conductive parts.

5 Mechanical drawings

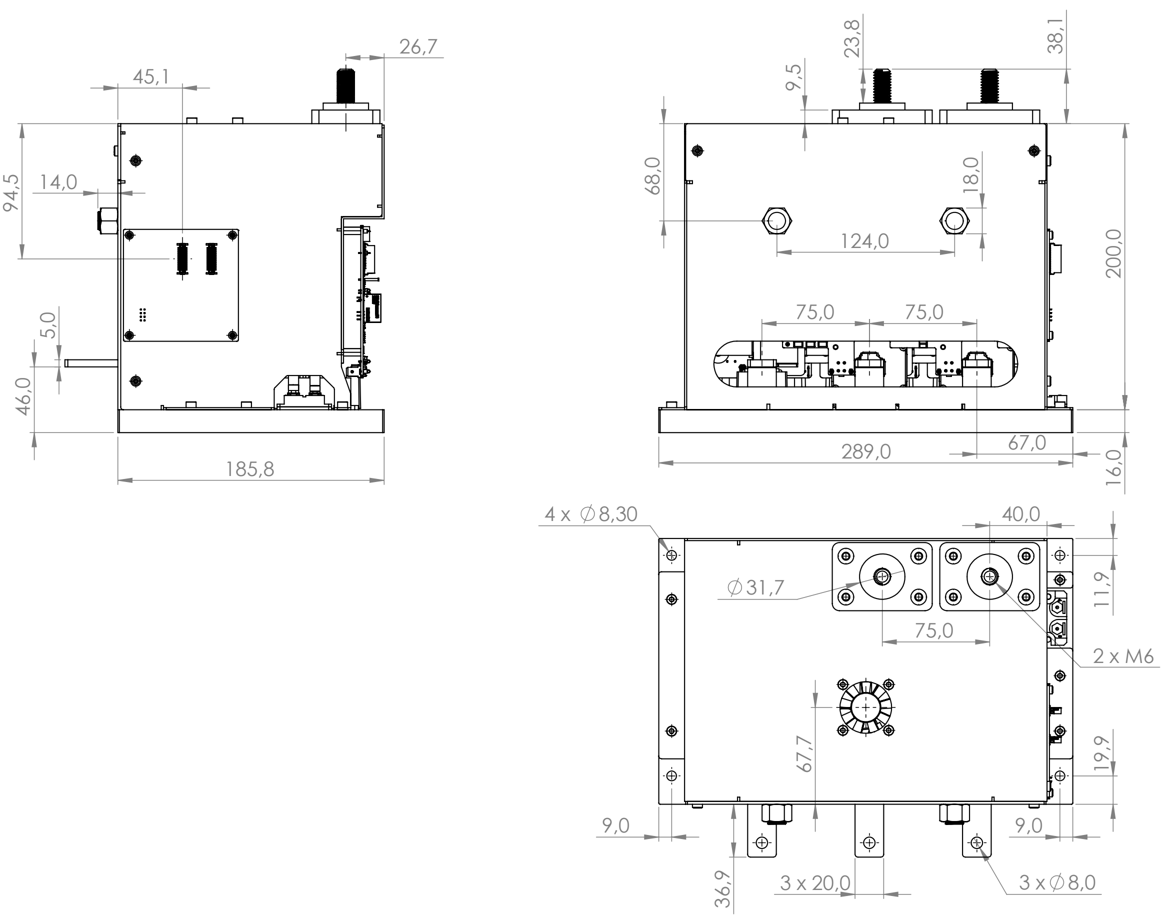

Figure 15: PCO-170T800 Mechanical drawings.

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