Control integrated power system (CIPOS™)

CIPOS™ Mini PFC-integrated IPM IM564 series: technical description

About this document

Scope and purpose

The scope of this application note is to describe the CIPOS™ Mini, an intelligent power module (IPM) with integrated power factor correction (PFC), and the basic requirements for operating the products in a recommended mode. This includes the integrated components, such as IGBTs or gate driver IC as well as the design of the necessary external circuitry, such as bootstrap or interfacing.

Intended audience

Power electronics engineers who want to design reliable and efficient CIPOS™ Mini PFC-integrated IPM applications.

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1 Scope

The scope of this application note is to describe the CIPOS™ Mini PFC-integrated IPM IM564 series and the basic requirements for operating the product in recommended conditions. This includes the integrated components, such as IGBTs or gate drive IC as well as the design of the necessary external circuitry, such as bootstrap or interfacing. Integrating discrete power semiconductors and drivers into one package enables the reduction of time and effort spent on design. To meet the strong demand for small size and higher power density, Infineon has developed a new family of highly integrated intelligent power modules that contain nearly all of the semiconductor components required to drive electronically controlled variable-speed electric motors. They incorporate a three-phase inverter and PFC power stage with a silicon-on-insulator (SOI) gate driver and Infineon's leading-edge TRENCHSTOP™ IGBTs and anti-parallel diodes for inverter part and 600 V CoolMOS™ superjunction MOSFET and rapid-switching, emitter-controlled diode for single boost PFC part.

The application note concerns the following products.

IM564-X6D

IM564-X6DS

Note: IM564-abcd
*a = **current scale**(X(20 A))*
*b = **6**(600 V)*
*c = **D**(DCB)*
*d = **options**(S(stand-off))*

CIPOS™ Mini PFC-integrated IPM is a family of intelligent power modules with single phase boost PFC which are designed for low-power motor drives in household appliances, such as air conditioners.

1.1 Product line-up

Table 1 Line-up of IM564 series

Part Number	Rating		Inverter circuit	PFC topology	Package	Isolation voltage (V_{rms})	Main applications
	Current [A]	Voltage [V]					
IM564-X6D IM564-X6DS	20	600	Closed emitter	Single phase boost	DCB DIL module	2000 V_{rms} sinusoidal, 1 min.	Air conditioner

1.2 Nomenclature

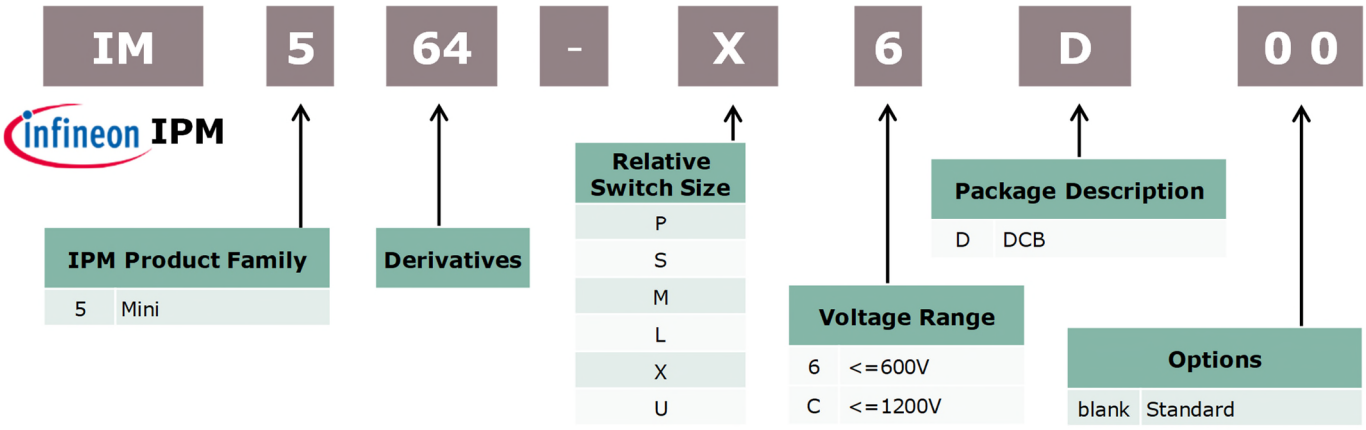


Figure 1 CIPOS™ Mini PFC-integrated IPM products nomenclature

2 Internal components and package technology

2.1 Power transistor technology for inverter

Infineon introduced TRENCHSTOP™ IGBT technology in 2004. This technology continues to make use of the well-known properties of robustness of Infineon IGBT, such as short-circuit withstand capability and maximum junction temperature. In addition, all advantages of these technologies remain in order to achieve highest efficiency, and enable highest power density. This refers to very low static parameters such as saturation voltage of IGBT as well as to excellent dynamic parameters such as turn-off energy of the IGBT [1].

2.2 Power diode technology for inverter

The emitter-controlled diode is Infineon's unique, fast-recovery diode technology. The ultra-thin wafer and fieldstop technology makes the emitter-controlled diode ideally suited for consumer and industry applications, as it lowers the turn-on losses of the IGBT with soft recovery. The emitter-controlled diode is optimized for Infineon IGBT technology.

2.3 Power transistor technology for PFC

The 600 V CoolMOS™ P7 superjunction MOSFET family is Infineon’s most well-balanced CoolMOS™ technology in terms of combining ease-of-use and excellent efficiency performance. Compared to its predecessors, this family offers highest efficiency and improved power density due to the significantly reduced gate charge and stored energy in output capacitance, as well as optimized on-resistance. The carefully selected integrated gate resistors enable very low ringing tendency.

2.4 Power diode technology for PFC

The rapid emitter-controlled diode of Infineon is optimized to operate as a boost diode in PFC stage. An advancement in thin-wafer technology helps to maintain a stable V_F over temperature. The rapid diode combines low V_F for lower conduction losses and low I_{RR} to reduce E_{ON} of the PFC MOSFET. Increased efficiency, with the additional benefit of having a 650 V breakdown voltage can be achieved [4].

2.5 Control IC – Six-channel gate driver IC

The basic feature of this technology is the separation of the active silicon from the base material by means of a buried silicon oxide layer. The buried silicon oxide provides an insulation barrier between the active layer and silicon substrate, and hence reduces the parasitic capacitance tremendously. Moreover, this insulation barrier disables leakage or latch-up currents between adjacent devices. This also prevents the latch-up effect even in the case of high dv/dt switching under elevated temperature, thus providing improved robustness. Besides, the thin-film SOI technology provides additional benefits like lower power consumption and higher immunity to radioactive radiation or cosmic rays [5]. A monolithic single control IC for all 6 IGBTs provides further advantages, such as bootstrap circuitry, matched propagation delay times, built-in deadtime, and cross-conduction prevention. In addition, all 6 IGBTs turn off under fault situations like undervoltage lockout (UVLO) or overcurrent.

2.6 Thermistor

In CIPOS™ Mini family, the thermistor is integrated optionally on the internal PCB. It is connected between V_{FO} and V_{SS} pins. A circuit proposal using the thermistor for over temperature protection is discussed in section 5.4.

Table 2 Raw data of the thermistor used in IM564 series

T [°C]	R_{min} [kΩ]	R_{typ} [kΩ]	R_{max} [kΩ]	Tol [%]	T [°C]	R_{min} [kΩ]	R_{typ} [kΩ]	R_{max} [kΩ]	Tol [%]
-40	2662.292	2962.540	3262.789	10.1	45	34.520	36.508	38.496	5.4
-35	1925.308	2133.692	2342.076	9.8	50	28.400	29.972	31.545	5.2
-30	1407.191	1553.414	1699.637	9.4	55	23.485	24.735	25.985	5.1
-25	1038.949	1142.63	1246.312	9.1	60	19.517	20.515	21.514	4.9
-20	774.497	848.747	922.997	8.7	65	16.296	17.097	17.898	4.7
-15	582.690	636.369	690.048	8.4	70	13.670	14.315	14.960	4.5
-10	442.252	481.410	520.568	8.1	75	11.517	12.039	12.561	4.3
-5	338.491	367.303	396.114	7.8	80	9.745	10.169	10.593	4.2
0	261.164	282.537	303.910	7.6	85	8.279	8.625	8.971	4.0
5	203.056	219.036	235.016	7.3	90	7.062	7.345	7.628	3.9
10	159.044	171.081	183.118	7.0	95	6.046	6.279	6.511	3.7
15	125.454	134.586	143.717	6.8	100	5.199	5.388	5.576	3.5
20	99.630	106.605	113.580	6.5	105	4.468	4.640	4.811	3.7
25	79.638	85.000	90.362	6.3	110	3.856	4.009	4.163	3.8
30	64.055	68.203	72.352	6.1	115	3.338	3.477	3.615	4.0
35	51.831	55.059	58.287	5.9	120	2.900	3.024	3.149	4.1
40	42.182	44.708	47.235	5.7	125	2.527	2.639	2.751	4.2

2.7 Package technology

The CIPOS™ Mini DCB package offers the smallest size while providing high-power density by employing inverter and PFC stages together. It contains all the power components and isolates them from each other and from the heat sink. All low power components such as the gate drive IC and thermistor are assembled on a PCB.

The electric insulation is provided by a ceramic layer of the DCB itself, which is simultaneously the thermal contact to the heat sink. In order to further decrease the thermal impedance, the internal lead frame design is optimized [6]. Figure 2 shows the external view of CIPOS™ Mini DCB package.

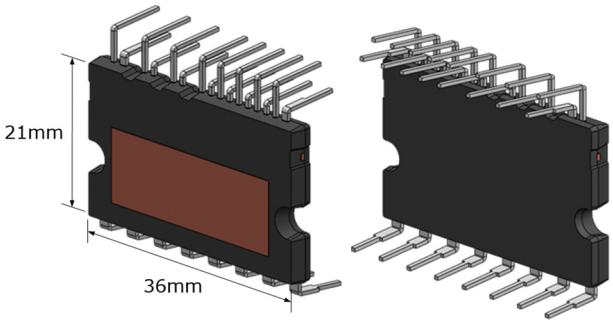


Figure 2 External view of CIPOS™ Mini DCB package

3 Product overview

3.1 Internal circuit and features

Figure 3 illustrates the internal block diagram of the CIPOS™ Mini PFC-integrated IPM. It consists of a three-phase IGBT inverter circuit, single-phase boost PFC circuit, and a driver IC with control functions. The detailed features and integrated functions of this IPM are described as follows.

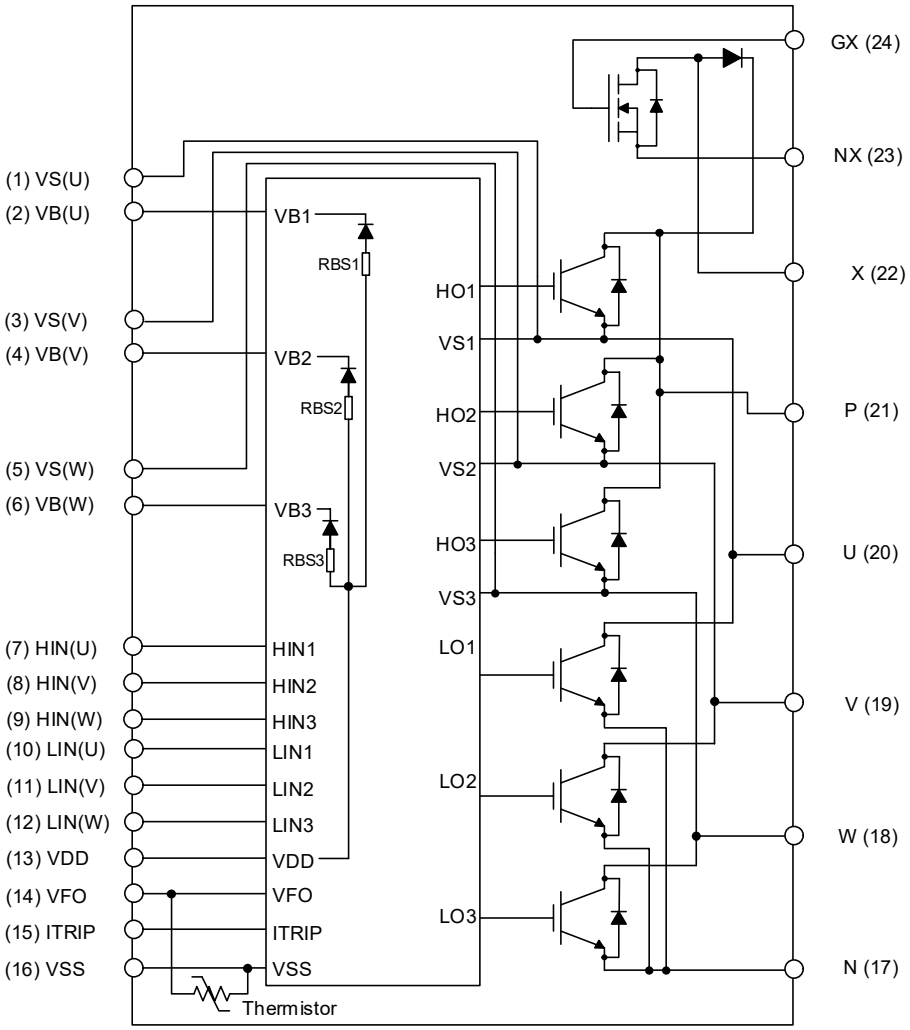


Figure 3 Internal circuit

- Package
  - Fully isolated dual in-line (DIL) molded module
  - Lead-free terminal plating; RoHS-compliant
  - Very low thermal resistance thanks to DCB
- Inverter
  - TRENCHSTOP™ IGBTs with separate freewheeling diode
  - Rugged SOI gate driver technology with stability against transient and negative voltage
  - Integrated bootstrap functionality
  - Matched delay times of all channels
  - Built-in deadtime

- PFC
  - CoolMOS™ MOSFET
  - 650 V rapid-switching emitter-controlled diode
- SOI gate driver functions
  - Overcurrent shutdown
  - Temperature monitor
  - Undervoltage lockout at all channels
  - Low-side closed emitter
  - Anti cross-conduction
  - All 6 switches turn off during protection
  - Active-high input signal logic

3.2 Maximum electrical ratings

Table 3 Detailed description of absolute maximum ratings (inverter part of IM564-X6D)

Item	Symbol	Rating	Description
Max. blocking voltage	V_{CES}	600 V	The sustained collector-emitter voltage of internal IGBTs
Continuous collector current	I_C	±20 A	The allowable continuous IGBT current at T_C = 25°C
Junction temperature	T_J	-40 ~ 150°C	Considering temperature ripple on the power chips, the maximum junction temperature rating of CIPOS™ Mini is 150°C.
Operating case temperature range	T_C	-40 ~ 125°C	Tc (case temperature) is defined as a temperature of the package surface underneath the specified power chip. Please mount a temperature sensor on a heat sink surface at the defined position in Figure 4 to get accurate temperature information.

Table 4 Detailed description of absolute maximum ratings (PFC part of IM564-X6D)

Item	Symbol	Rating	Description
Max. blocking voltage	V_{DSS}	600 V	The sustained drain-source voltage of PFC MOSFET
Gate-source voltage	V_{GS}	±20 V	The allowable peak MOSFET gate-source voltage
Continuous drain current	I_D	20 A	The allowable continuous MOSFET current at T_C = 25°C
Junction temperature	T_J	-40 ~ 150°C	Considering temperature ripple on the power chips, the maximum junction temperature rating of CIPOS™ Mini is 150°C.

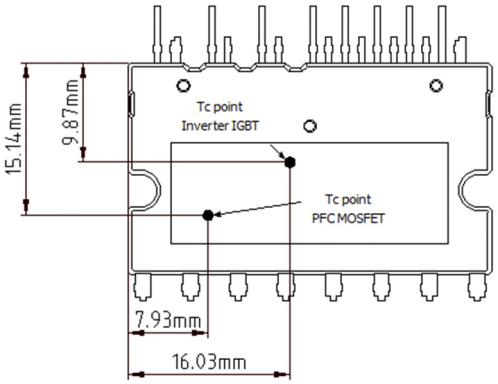


Figure 4 T_C measurement point of IM564-X6D

3.3 Maximum electrical ratings

Table 5 defines the CIPOS™ Mini PFC-integrated IPM input and output pins. The detailed functional descriptions are as follows:

Table 5 Pin description of IM564 series

Pin number	Pin name	Pin description
1	VS(U)	U-phase high-side floating IC supply offset voltage
2	VB(U)	U-phase high-side floating IC supply voltage
3	VS(V)	V-phase high-side floating IC supply offset voltage
4	VB(V)	V-phase high-side floating IC supply voltage
5	VS(W)	W-phase high-side floating IC supply offset voltage
6	VB(W)	W-phase high-side floating IC supply voltage
7	HIN(U)	U-phase high-side gate driver input
8	HIN(V)	V-phase high-side gate driver input
9	HIN(W)	W-phase high-side gate driver input
10	LIN(U)	U-phase low-side gate driver input
11	LIN(V)	V-phase low-side gate driver input
12	LIN(W)	W-phase low-side gate driver input
13	V_{DD}	Low-side control supply
14	V_{FO}	Fault output / Temperature monitor
15	ITRIP	Overcurrent shutdown input
16	V_{SS}	Low-side control negative supply
17	N	Inverter low-side emitter
18	W	Motor W-phase output
19	V	Motor V-phase output
20	U	Motor U-phase output
21	P	Positive PFC output voltage / Positive inverter bus input voltage
22	X	PFC MOSFET drain
23	NX	PFC MOSFET source
24	GX	PFC MOSFET gate

High-side bias voltage pins for driving the IGBT

Pins: VB(U) – VS(U) , VB(V) – VS(V), VB(W) – VS(W)

- These pins provide the gate drive power to the high-side IGBTs.
- The ability to utilize a bootstrap circuit scheme for the high-side IGBTs eliminates the need for external power supplies.
- Each bootstrap capacitor is charged from the V_{DD} supply during the ON-state of the corresponding low-side IGBT or the freewheeling state of the low-side freewheeling diode.
- In order to prevent malfunctions caused by noise and ripple in the supply voltage, a good quality (low ESR, low ESL) filter capacitor should be mounted very close to these pins.

Low-side bias voltage pin

Pin: V_{DD}

- This is the control supply pin for the internal IC.
- In order to prevent malfunctions caused by noise and ripple in the supply voltage, a good quality (low ESR, low ESL) filter capacitor should be mounted very close to this pin.

Low-side common supply ground pin

Pin: VSS

- This pin connects the control ground for the internal IC.

Signal input pins

Pins: HIN(U), HIN(V), HIN(W), LIN(U), LIN(V), LIN(W)

- These are pins to control the operation of the internal IGBTs.
- They are activated by voltage input signals. The terminals are internally connected to a Schmitt trigger circuit composed of 5V-class CMOS.
- The signal logic of these pins is active-high. The IGBT associated with each of these pins will be turned "ON" when a sufficient logic voltage is applied to these pins.
- The wiring of each input should be as short as possible to protect the CIPOS™ Mini against noise influences
- To prevent signal oscillations, an RC filter is recommended as illustrated in Figure 6.

Overcurrent detection pin

Pin: ITRIP

- The current sensing shunt resistor should be connected between the pin N (emitter of low-side IGBT) and the power ground to detect short-circuit current (refer to Figure 8). An RC filter should be connected between the shunt resistor and the pin ITRIP to eliminate noise.
- The integrated comparator is triggered if the voltage V_{ITRIP} is higher than 0.525 V. The shunt resistor should be selected to meet this level for the specific application. In case of a trigger event, the voltage at pin V_{FO} pin is pulled down to LOW.
- The connection length between the shunt resistor and ITRIP pin should be minimized.

Fault output and temperature-monitoring pin

Pin: V_{FO}

- This is the fault output alarm pin. An active-low output is given on this pin for a fault state condition in the CIPOS™ Mini. The alarm conditions are overcurrent detection and low-side bias undervoltage operation.
- The V_{FO} output is open-drain configured. The V_{FO} signal line should be pulled up to the logic power supply (5V / 3.3V) with proper resistance considering temperature monitoring with the parallel-connected thermistor between V_{FO} and V_{SS} pins optional.

Positive DC-link pin

Pin: P

- This is the DC-link positive power supply pin of the CIPOS™ Mini PFC-integrated IPM.
- It is internally connected to the collectors of the high-side IGBTs.
- In order to suppress the surge voltage caused by the DC-link wiring or PCB pattern inductance, connect a smoothing filter capacitor close to this pin. (Typically, metal film capacitors are used.)

Negative DC-link pin

Pin: N

- This is the DC-link negative power supply pin (power ground) of the inverter.
- This pin is connected to the low-side IGBT emitters of the each phase.

Inverter power output pins

Pins: U, V, W

- Inverter output pins for connecting to the inverter load (e. g. motor).

Single-phase boost PFC pins

Pins: X, NX, GX

- These pins are drain, source and gate of MOSFET for single-phase boost PFC.

3.4 Outline drawing

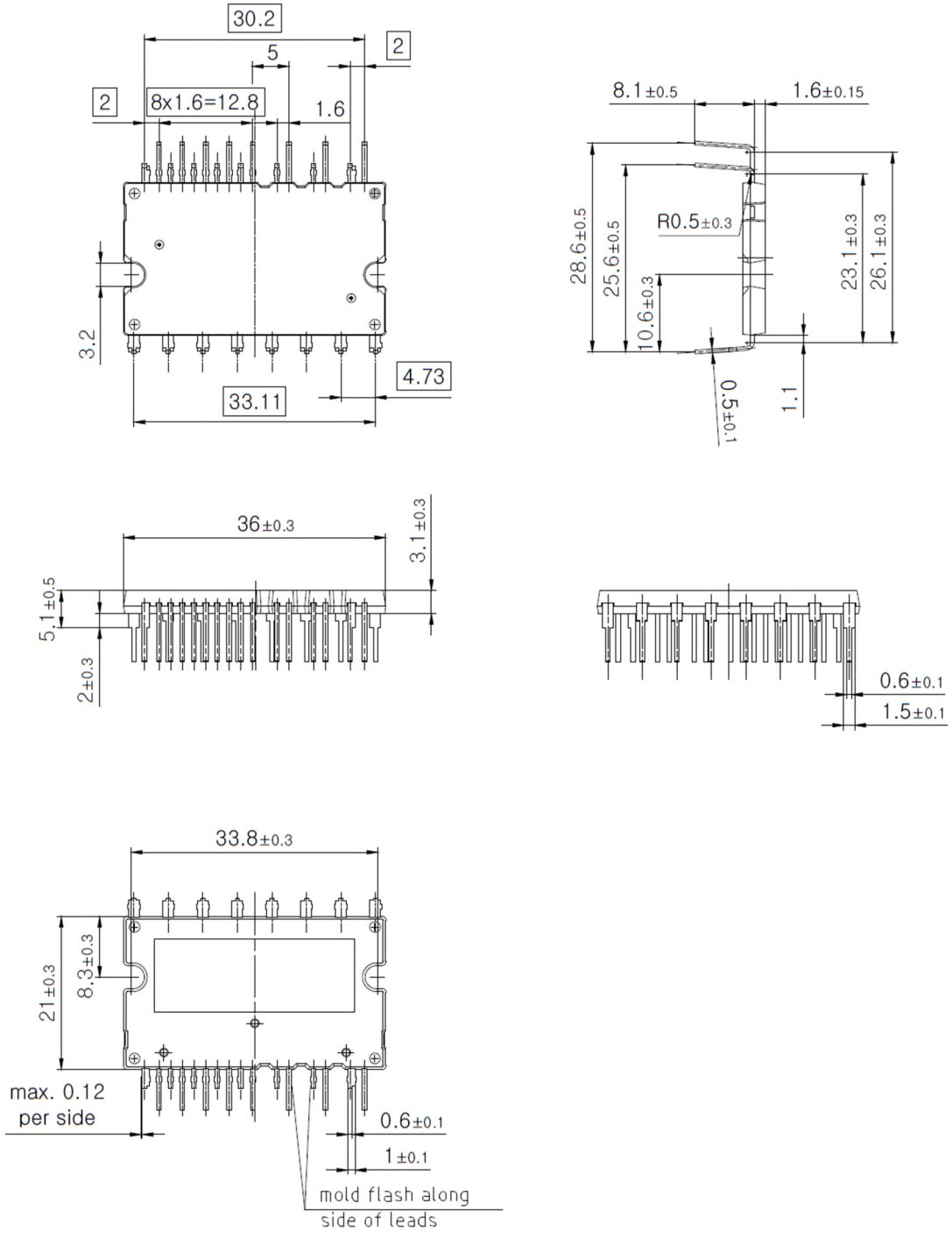


Figure 5 Package outline dimensions of IM564-X6D (unit: [mm])

4 Interface circuit and layout guide

4.1 Input and output signal connection

Figure 6 shows the I/O interface circuit between microcontroller and the CIPOS™ Mini. The CIPOS™ Mini input logic is active-high with internal pull-down resistors. External pull-down resistors are not needed. V_{FO} output is open-drain configured. This signal should be pulled up to the positive side of 5 V or 3.3 V external logic power supply with a pull-up resistor. The pull-up resistor value should be properly selected, e.g. 3.6 kΩ with a parallel connected thermistor between V_{FO} and V_{SS} pins.

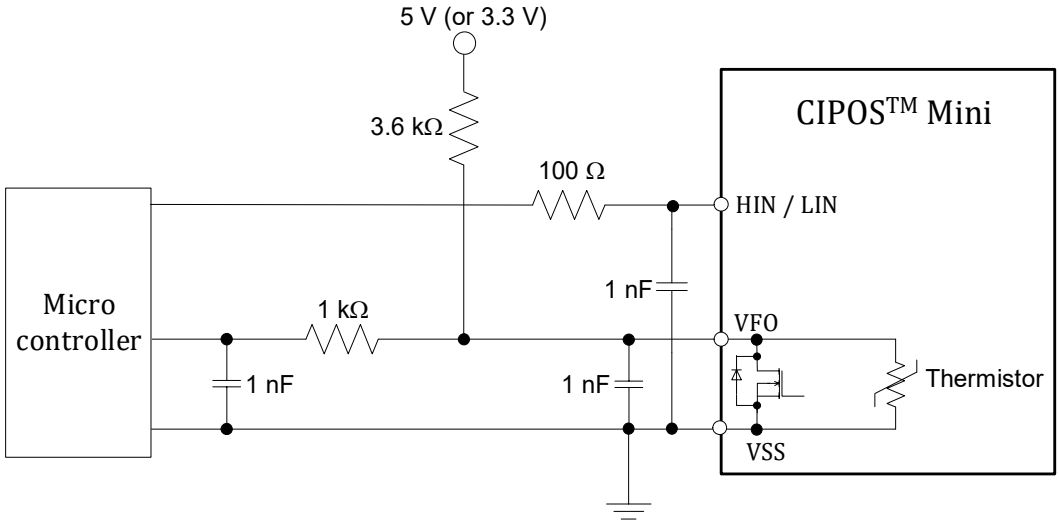


Figure 6 Recommended microcontroller I/O interface circuit

Table 6 Maximum ratings of input and V_{FO} pins

Item	Symbol	Condition	Rating	Unit
Module supply voltage	V_{DD}	Applied between V_{DD} – V_{SS}	20	V
Input voltage	VIN	Applied between HIN(U), HIN(V), HIN(W) – V_{SS} LIN(U), LIN(V), LIN(W) – V_{SS}	-5.5 ~ V_{DD}+0.5	V
Fault output supply voltage	V_{FO}	Applied between V_{FO} – V_{SS}	-0.5 ~ V_{DD}+0.5	V

The input and fault output maximum rating voltages are listed in Table 6. Since the fault output is open-drain configured and its rating is V_{DD}+0.5 V, a 15 V supply interface is possible. However, it is recommended that the fault output be configured with the 5 V logic supply, which is the same as the input signals. It is also recommended to place bypass capacitors as close as possible to the V_{FO} and signal lines from the microcontroller as well as to the CIPOS™ Mini.

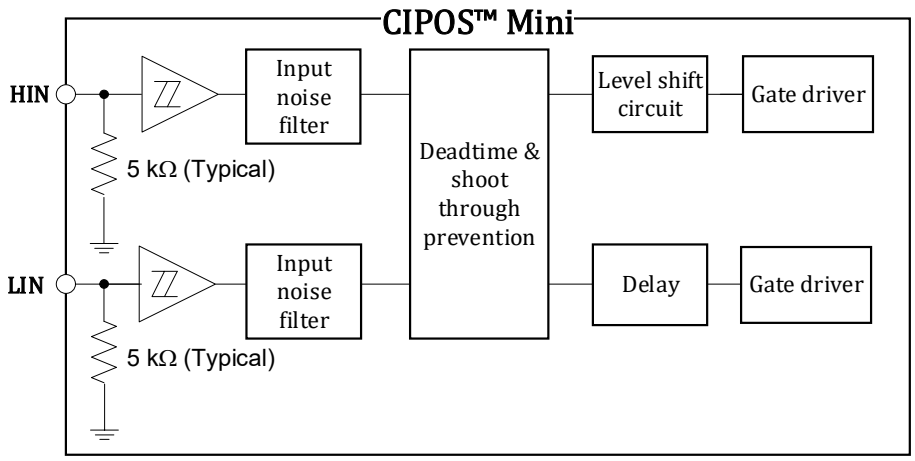


Figure 7 Simplified block diagram of CIPOS™ Mini control IC

Because the CIPOS™ Mini family employs active-high input logic, the power sequence restriction between the control supply and the input signal during start-up or shut-down operation does not exist. Therefore it makes the system fail-safe. In addition, pull-down resistors are built into each input circuit. Thus, external pull-down resistors are not needed. This reduces the required external component count. Input Schmitt triggers, noise filters, deadtime and shoot-through prevention functions provide beneficial noise rejection to short input pulses. Furthermore, by lowering the turn-on and turn-off threshold voltage of the input signal as shown in Table 7, a direct connection to 3.3 V-class microcontroller or DSP is possible.

Table 7 Input threshold voltage (at V_{DD} = 15 V, T_J = 25℃)

Item	Symbol	Condition	Min.	Typ.	Max.	Unit
Logic "1" input voltage (LIN, HIN)	V_{IH_TH}	HIN – V_{SS} LIN – V_{SS}	1.7	2.0	2.3	V
Logic "0" input voltage (LIN, HIN)	V_{IL_TH}		0.7	0.9	1.1	V

As shown in Figure 7, the CIPOS™ Mini input signal section integrates a 5 kΩ (typical) pull-down resistor. Therefore, when using an external filtering resistor between microcontroller output and CIPOS™ Mini input, pay attention to the signal voltage drop at the CIPOS™ Mini input terminals. It should fulfill the logic "1" input voltage requirement. For instance, R = 100 Ω and C = 1 nF for the parts shown in Figure 6.

4.2 General interface circuit example

Figure 8 shows typical application circuit of CIPOS™ Mini PFC-integrated IPM for interface schematic with control signals connected directly to a microcontroller.

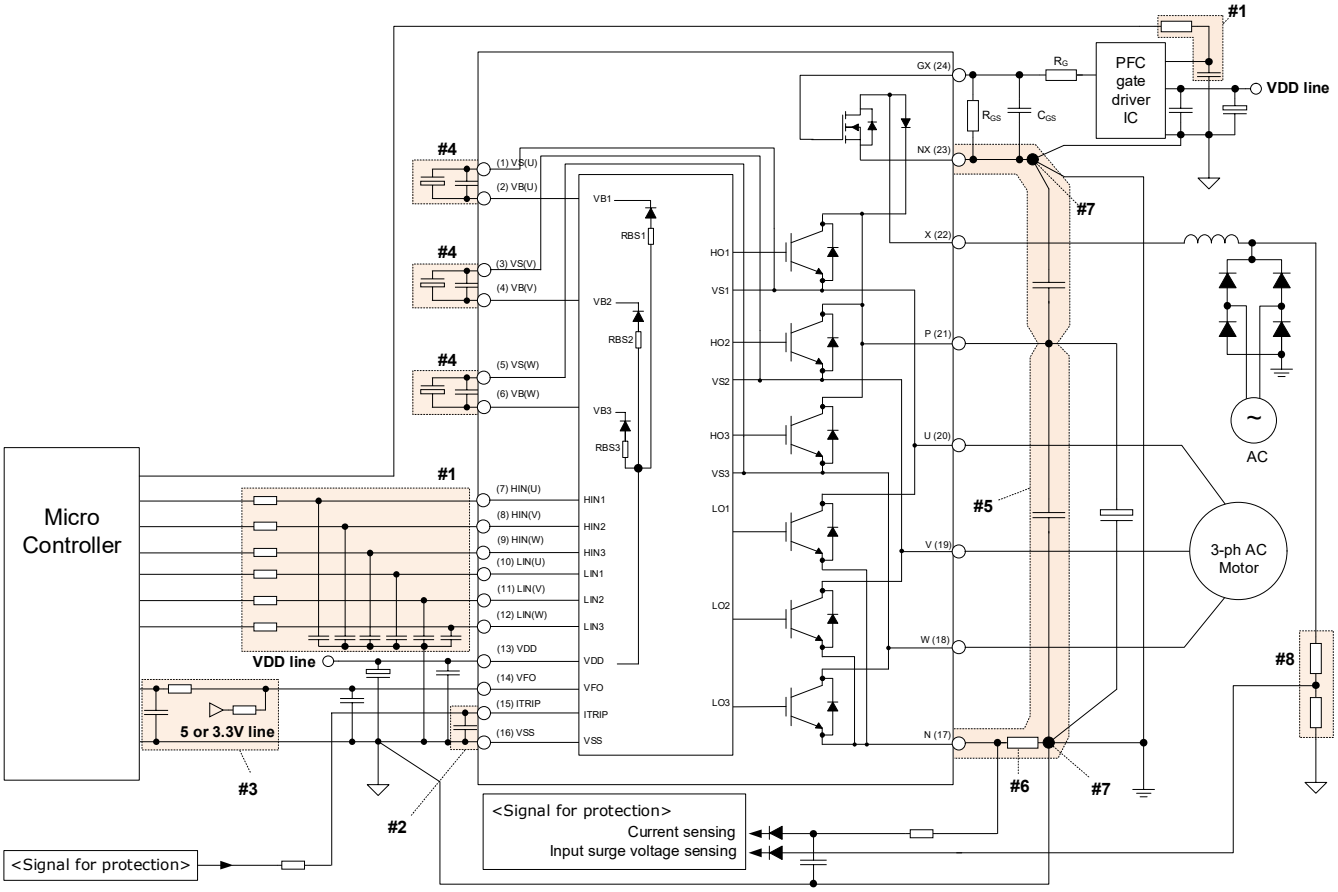


Figure 8 Application circuit example

Because the PFC MOSFET inside this product has very high-speed switching characteristics, considerably large surge voltage between P and NX terminals, and switching noise on signaling path are generated easily. Please pay attention to the items below for optimized application circuit design:

1. *Input circuit*
   - *To reduce input signal noise by high-speed switching, RC filter circuit can be used. (e.g. 100 Ω, 1 nF).*
   - *The filter capacitor should be placed as close to V_{SS} pin as possible.*
2. *ITRIP circuit*
   - *To prevent protection function errors, RC filter circuit is recommended.*
   - *The filter capacitor should be placed as close to ITRIP and V_{SS} pins as possible.*
3. *V_{FO} circuit*
   - *V_{FO} is an open-drain output. This signal line should be pulled up to the positive side of the 5 V/3.3 V logic power supply with a proper resistor.*
   - *It is recommended that the RC filter be placed as close to the controller as possible.*
4. *VB-VS circuit*
   - *Capacitors for high-side floating supply voltage should be placed as close to VB and VS pins as possible.*
5. *Snubber capacitor*

- *The wiring between CIPOS™ Mini and snubber capacitor including shunt resistor should be as short as possible.*

6. *Shunt resistor*
   - *SMD-type resistor is strongly recommended to minimize stray inductance.*
7. *Ground pattern*
   - *Each ground pattern should be connected at a single point.*
   - *Power ground pattern between PFC and inverter should be connected as short as possible.*
8. *Input surge voltage protection circuit*
   - *This protection circuit is recommended for PFC MOSFET to be protected from excessive surge voltage.*

4.3 Rated output current of control power supply

Control and gate drive power for the CIPOS™ Mini is normally provided by a single 15 V supply that is connected to the module V_{DD} and V_{SS} terminals. Also, we have to consider PFC MOSFET power consumption. The circuit current of V_{DD} control supply of IM564-X6D is shown in Table 8 (a), (b).

Table 8 The circuit current of control power supply (IM564-X6D)

(a) Inverter section

Condition		Current
V_{DD} = 15 V	f_{SW} = 5 kHz	6.0 mA
	f_{SW} = 20 kHz	17.7 mA

(b) PFC section with gate drive IC (IR44272L)

Condition		Current
V_{DD} = 15 V	f_{SW} = 20 kHz	8.7 mA
V_{DD} = 15 V	f_{SW} = 100 kHz	41.1 mA

The circuit current of the 5 V logic power supply (V_{FO} & input terminals) is about 20 mA.

Finally, the recommended minimum circuit currents of the power supply are shown in Table 9, which is considered ripple current with sufficient margins at the worst conditions, e.g. 5 times higher than the calculated value.

Table 9 The recommended minimum circuit current of control power supply (IM564-X6D)

Item	The circuit current of +15 V control supply	The circuit current of +5 V logic supply
$V_{DD} \leq$ 15 V, $f_{SW} \leq$ 20 kHz	130 mA	45 mA

4.4 Layout for overcurrent protection (OCP) and short-circuit protection (SCP) function

It is recommended that the ITRIP filter capacitor connections to the CIPOS™ Mini pins should be as short as possible. The ITRIP filter capacitor should be connected to V_{SS} pin directly without overlapped ground pattern. The signal ground and power ground should be as short as possible and connected at only one point via the filter capacitor of V_{DD} line.

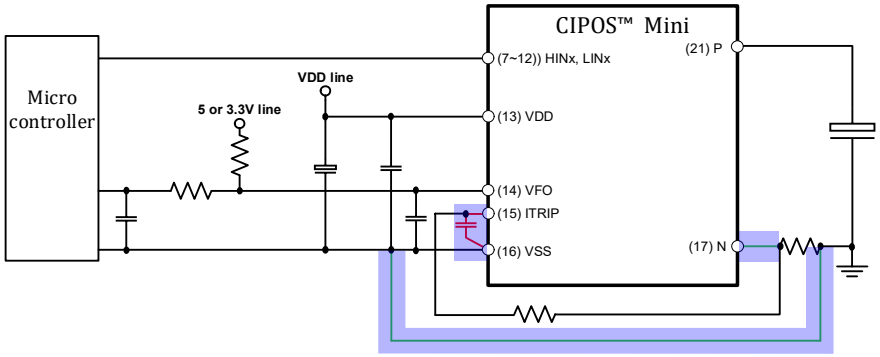


Figure 9 Recommended layout for OCP and SCP function

4.5 Shunt resistor and snubber capacitor location

An external current sensing resistor is applied to detect overcurrent of phase currents. A long pattern between the shunt resistor and CIPOS™ Mini will cause excessive surges that might damage the CIPOS™ Mini's internal IC and current detection components. This may also distort the sensing signal. To decrease the pattern inductance, the connection between the shunt resistor and CIPOS™ Mini should be as short as possible. As shown in Figure 10, a snubber capacitor should be put in the right place so as to suppress surge voltages effectively. Generally a high-frequency, non-inductive capacitor of around 0.1 ~ 0.22 µF is recommended. If the snubber capacitor location is not good as '1' in Figure 10, the snubber capacitor cannot suppress the surge voltage effectively. If the capacitor is placed at '2', the charging and discharging currents generated by parasitic inductance and the snubber capacitor will appear on the shunt resistor. This will impact the current-sensing signal and the short-circuit protection level will be a little lower than the calculated design value. Although the surge-suppression effect is better with location '2' than '3', the '3' is a reasonable compromise with better suppression without impacting the current-sensing signal accuracy. For this reason, location '3' is generally used.

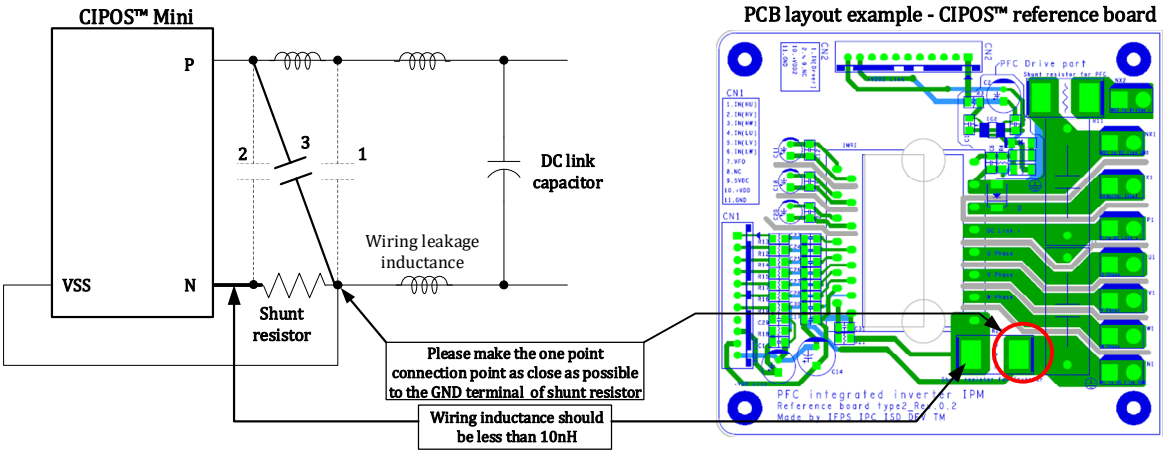


Figure 10 Recommended location of shunt resistor and snubber capacitor

4.6 Layout for gate driving of PFC MOSFET

We should consider PCB pattern layout carefully when drawing the layout for the PFC gate drive cicuit. Because the PFC MOSFET is operated at high frequency, stable PFC MOSFET operation is dependent on the pattern layout of the gate drive circuit. Especially, the ground pattern design is important.

In order to prevent interference of the PFC gate signal by MOSFET switching, we recommend the pattern design “2” and “4” in Figure 11. It is recommended to make a single point connection between the ground of the gate driver and the power ground as showin in the red circle in Figure 11. If PCB pattern is desgined as “1” and “3”, the PFC MOSFET might be operated improperly due to gate-voltage oscillation. Also, we recommend adding a capacitor across the PFC MOSFET gate and source for stable operation.

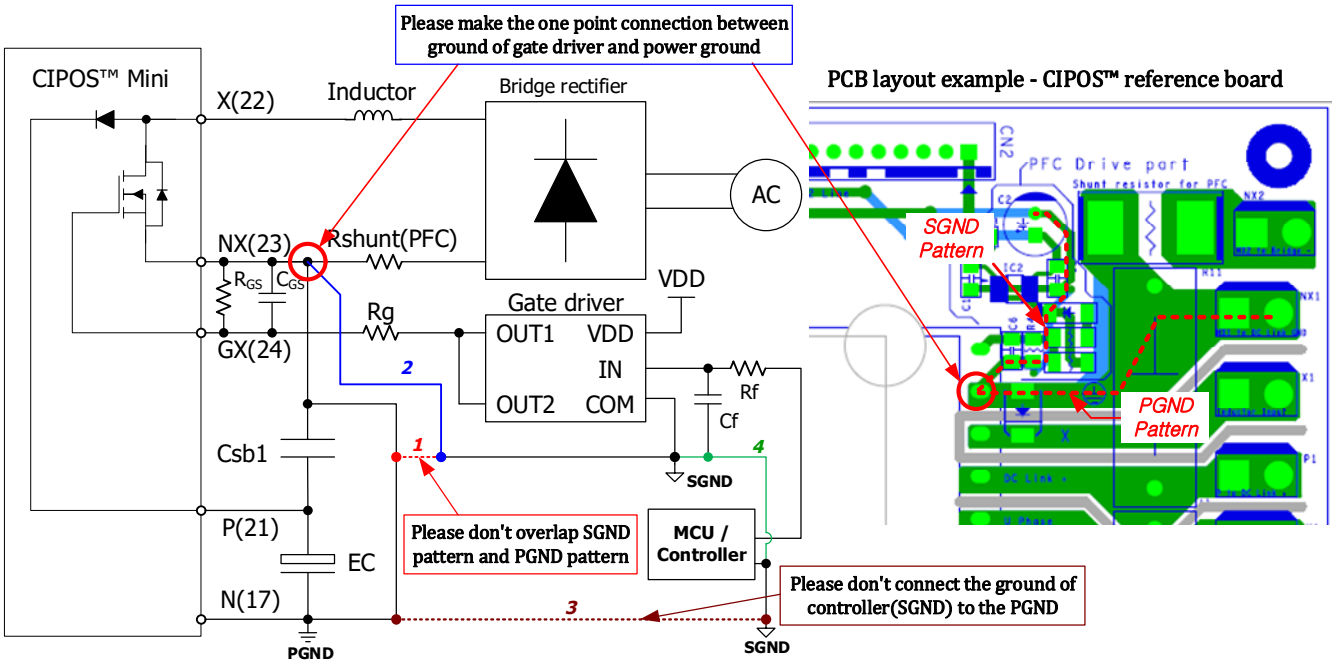


Figure 11 Recommended layout between signal ground (SGND) and power ground (PGND)

4.7 Pin and screw hole coordinates

Figure 12 shows CIPOS™ Mini package position on PCB to indicate center coordinates of each pin and screw hole in Table 10.

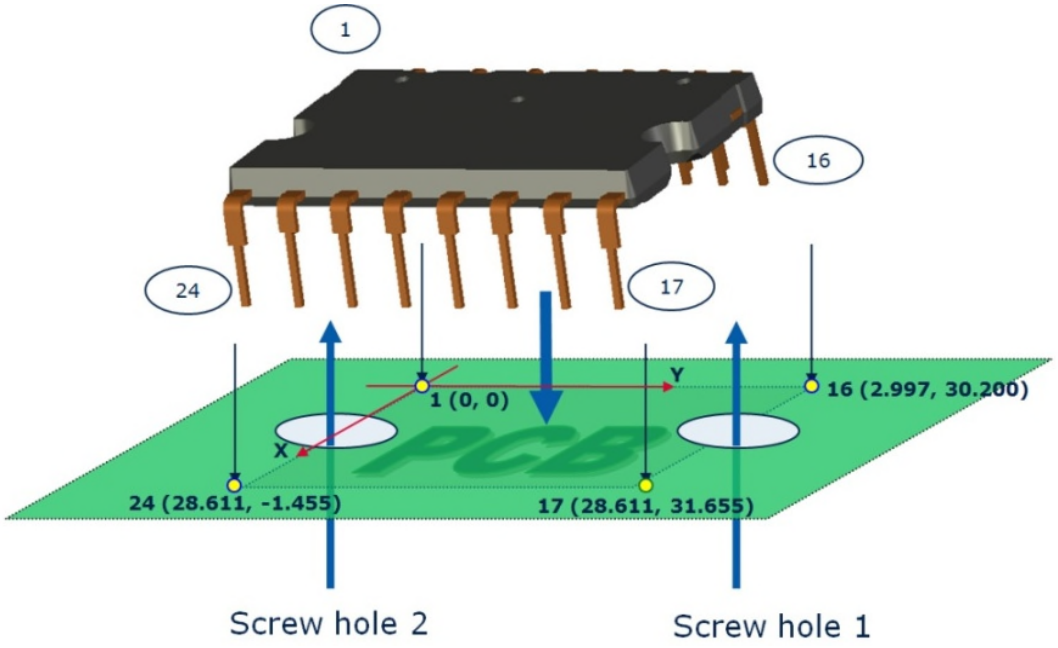


Figure 12 CIPOS™ Mini package position on PCB (unit: [mm])

Table 10 Pin and screw hole coordinates for CIPOS™ Mini package footprint (unit: [mm])

Pin number		X	Y	Pin number		X	Y
Signal pins	1	0.000	0.000	Signal pins	14	2.997	26.600
	2	2.997	2.000		15	0.000	28.200
	3	0.000	5.400		16	2.997	30.200
	4	2.997	7.000	Power pins	17	28.611	31.655
	5	0.000	10.400		18	28.611	26.925
	6	2.997	12.000		19	28.611	22.195
	7	0.000	15.400		20	28.611	17.465
	8	2.997	17.000		21	28.611	12.735
	9	0.000	18.600		22	28.611	8.005
	10	2.997	20.200		23	28.611	3.275
	11	0.000	21.800		24	28.611	-1.455
	12	2.997	23.400	Screw hole	25	17.950	32.000
	13	0.000	25.000		26	17.950	-1.800

5 Protection features

5.1 Undervoltage protection

Control and gate drive power for the CIPOS™ Mini is normally provided by a single 15 V supply that is connected to the module V_{DD} and V_{SS} terminals. For proper operation, this voltage should be regulated to 15 V ± 10%. Table 11 describes the behavior of the CIPOS™ Mini for various control supply voltages. The control supply should be well filtered with a low impedance electrolytic capacitor and a high-frequency decoupling capacitor connected at the CIPOS™ Mini's pins.

High-frequency noise on the supply might cause the internal control IC to malfunction and generate erroneous fault signals. To avoid these problems, the maximum ripple on the supply should be less than ± 1 V/µs.

The potential at the module's V_{SS} terminal is different from that at the N power terminal by the voltage drop across the sensing resistor. It is very important that all control circuits and power supplies be referred to this point and not to the N terminal. If circuits are improperly connected, the additional current flowing through the sense resistor might cause improper operation of the short-circuit protection function. In general, it is best practice to make the common reference (V_{SS}) a ground plane in the PCB layout.

The main control power supply is also connected to the bootstrap circuits to generate the floating supplies for the high-side gate drives.

When control supply voltage (V_{DD} and V_{BS}) falls down under UVLO level, IGBT will turn off while ignoring the input signal.

Table 11 CIPOS™ Mini functions versus control power supply voltage

Control voltage range [V]	CIPOS™ Mini function operations
0 ~ 13.1	Because the UVLO function is activated, control input signals are blocked and a fault signal V_{FO} is generated.
13.1 ~ 17.5	Normal operation. This is the recommended operating condition. V_{DD} of 14.5 ~ 17 V is recommended when only integrated bootstrap circuitry is used.
17.5 ~ 20	Because driving voltage is above the recommended range, the IGBT's switching is faster. It causes increased system noise. And peak short-circuit current might be too large for proper operation of the short-circuit protection. Operation in this V_{DD} range is not recommended.
Over 20	Control circuit in the CIPOS™ Mini might be damaged.

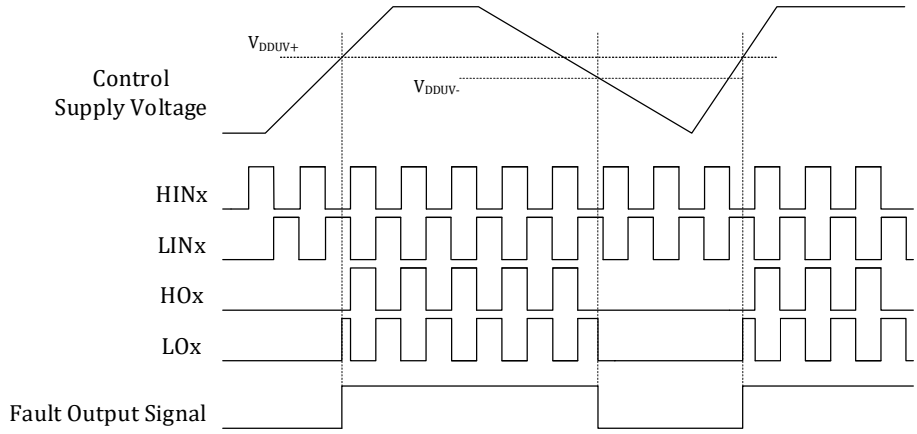


Figure 13 Timing chart of low-side UVLO protection function

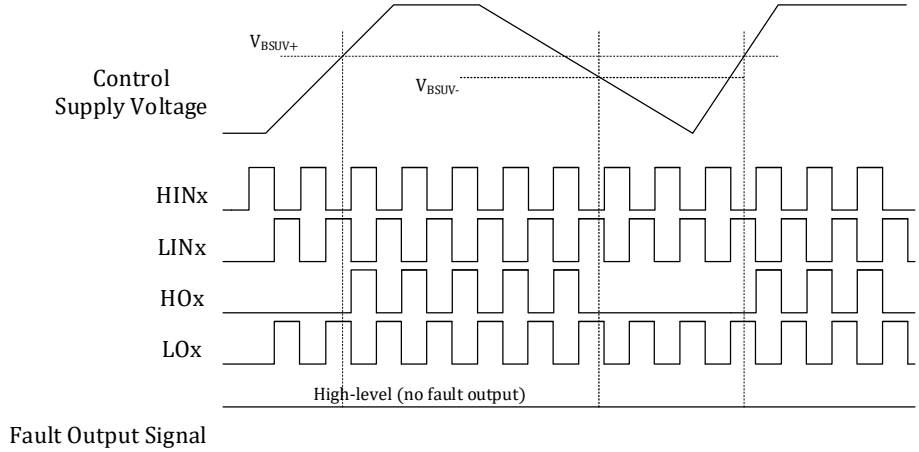


Figure 14 Timing chart of high-side UVLO protection function

5.2 Overcurrent protection

5.2.1 Timing chart of overcurrent (OC) protection

The CIPOS™ Mini has an overcurrent shutdown function. Its internal IC monitors the voltage of the ITRIP pin and if this voltage exceeds the $V_{IT,TH+}$, which is specified in the devices datasheets, a fault signal is activated and all IGBTs are turned off. Typically, the maximum short-circuit current magnitude is gate-voltage dependant. A higher gate voltage results in a higher short-circuit current. In order to avoid this potential problem, the maximum overcurrent trip level is generally set to below 2 times the nominal rated collector current. The overcurrent protection timing chart is shown in Figure 15.

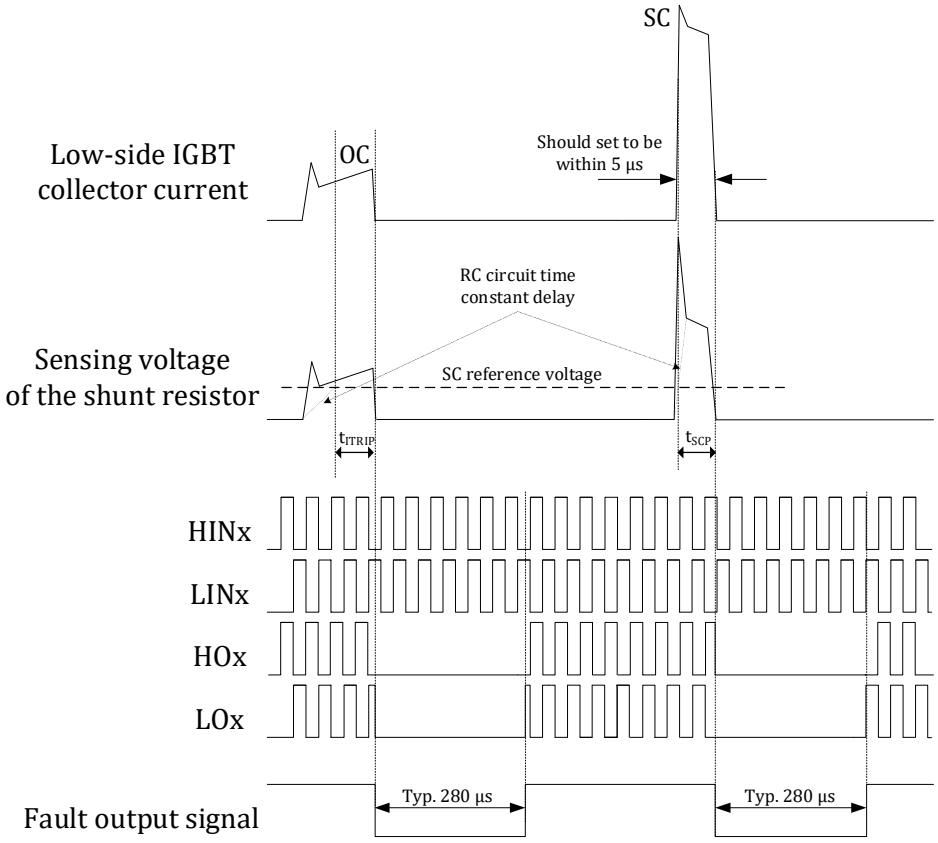


Figure 15 Timing chart of overcurrent protection function

5.2.2 Selecting current-sensing shunt resistor

The value of the current-sensing resistor is calculated by the following expression:

$$R_{SH} = \frac{V_{IT,TH+}}{I_{OC}} \quad (1)$$

Where $V_{IT,TH+}$ is the ITRIP positive going threshold voltage of CIPOS™ Mini. It is typically 0.525 V. I_{OC} is the current of overcurrent detection level.

The maximum value of the overcurrent protection level should be set lower than the repetitive peak collector current in the datasheet considering the tolerance of the shunt resistor.

As an example, the maximum peak collector current of IM564-X6D is 40 A_{peak}, and thus, the recommended value of the shunt resistor is calculated as

$$R_{SH(min)} = \frac{0.525}{40} = 0.013\ \Omega$$

For the power rating of the shunt resistor, the list below should be considered:

- Maximum load current of inverter (I_{RMS})
- Shunt resistor value at T_C = 25°C (R_{SH})
- Power derating ratio of shunt resistor at T_{SH} = 100°C according to the manufacturer's datasheet
- Safety margin

The shunt resistor power rating is calculated by the following equation.

$$P_{SH} = \frac{I_{RMS}{}^2 \times R_{SH} \times margin}{derating\ ratio} \quad (2)$$

An example in case of IM564-X6D and R_{SH} = 13 mΩ is as follows:

- Max. load current of the inverter: 10 A_{RMS}
- Power derating ratio of shunt resistor at T_{SH} = 100°C: 80%
- Safety margin: 30%

$$P_{SH} = \frac{10^2 \times 0.013 \times 1.3}{0.8} = 2.1\ W$$

A proper power rating of shunt resistor is over 2.1 W, e.g. 2.5 W.

Note that a proper resistance and power rating higher than the minimum value should be chosen considering the overcurrent protection level required in the application.

5.2.3 Delay time

The RC filter is necessary in the overcurrent sensing circuit to prevent the malfunction of overcurrent protection caused by noise. The RC time constant is determined by considering the noise duration and the short-circuit withstand time of the IGBT. When the sensing voltage on the shunt resistor exceeds the ITRIP positive-going threshold ($V_{IT,TH+}$), this voltage is applied to the ITRIP pin of CIPOS™ Mini via the RC filter. Table 12 shows the specification of the overcurrent protection reference level. There is delay time (t_{FILTER}) caused by the filter, and it can be calculated using equation (3) and (4).

$$V_{IT,TH+} = R_{SH} \cdot I_C \cdot \left(1 - \frac{1}{e^{\frac{t_{Filter}}{\tau}}}\right) \quad (3)$$

$$t_{Filter} = -\tau \cdot \ln(1 - \frac{V_{IT,TH+}}{R_{SH} \cdot I_C}) \quad (4)$$

Where, $V_{IT,TH+}$ is the ITRIP pin input voltage, I_C is the peak current, R_{SH} is the shunt resistor value and τ is the RC time constant. In addition there is a short-circuit propagation delay (t_{SCP}). Please refer to Table 13.

Table 12 Specification of OC protection reference level '$V_{IT.TH+}$'

Item	Min.	Typ.	Max.	Unit
ITRIP positive-going threshold $V_{IT,TH+}$	0.475	0.525	0.57	V

Table 13 Internal delay time of OC protection circuit

Item		Condition	Min.	Typ.	Max.	Unit
Short-circuit propagation delay (t_{SCP})	IM564-X6D	from $V_{IT,TH+}$ to 10% I_{SC}		1600		ns
	IM564-X6DS					

Therefore, the total delay becomes:

$$t_{Total} = t_{Filter} + t_{SCP} \quad (5)$$

The total delay must be less than the 5 µs of short-circuit withstand time (t_{SC}) in the datasheet. Thus, the RC time constant should be set in the range of 1~2 µs. Recommended values for the filter components are R = 1.8 kΩ and C = 1 nF.

5.3 Fault output circuit

Table 14 Fault output maximum ratings

Item	Symbol	Condition	Rating	Unit
Fault output supply voltage	V_{FO}	Applied between V_{FO}-V_{SS}	-0.5 ~ V_{DD} + 0.5	V
Fault output current	I_{FO}	Sink current at V_{FO} pin	10	mA

Table 15 Electric characteristics

Item	Symbol	Condition	Min.	Typ.	Max.	Unit
Fault output current	I_{FO}	V_{ITRIP} = 0 V, V_{FO} = 5 V	-	60	-	µA
Fault output voltage	V_{FO}	I_{FO} = 10 mA, V_{ITRIP} = 1 V	-	0.35	-	V

Because V_{FO} terminal is an open-drain type, it must be pulled up to the high level via a pull-up resistor. The resistor has to be calculated according to the above specifications.

5.4 Over-temperature protection

CIPOS™ Mini with optional temperature sensing function has one pin for both fault output and temperature sensing. Figure 16 shows the internal thermistor resistance characteristics as a function of the thermistor temperature. A circuitry is introduced in this section for over-temperature protection. As shown in Figure 17, the V_{FO} pin is connected directly to the analog-to-digital converter (ADC) and fault detection terminals of the microcontroller. This circuit is very simple and allows the IGBTs to be shut down by the microcontroller. As an example, when R1 is 3.6 kΩ and the thermistor temperature is 100°C, V_{FO} is 2.95 $V_{typ.}$ at Vctr = 5 V or 1.95 V at Vctr = 3.3 V, as shown in Figure 18. Noted that V_{FO} for over temperature protection should not be less than microcontroller fault trip level.

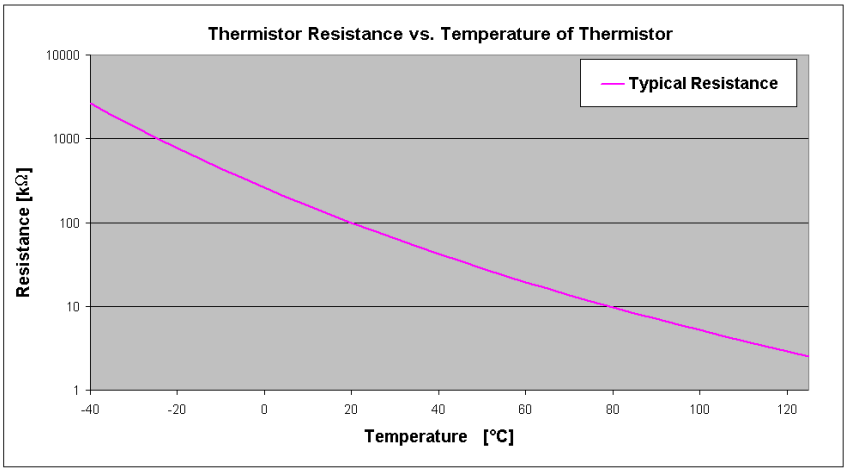


Figure 16 Internal thermistor resistance as a function of thermistor temperature

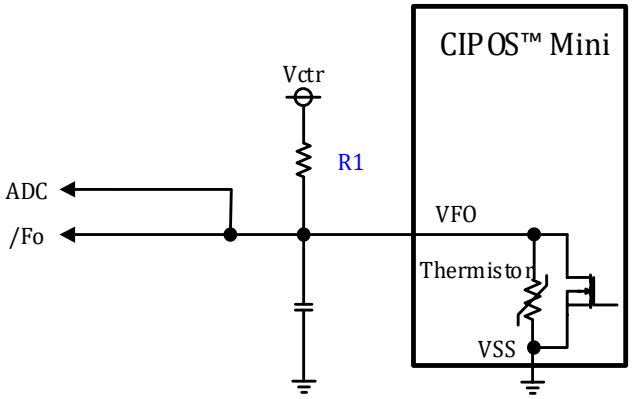


Figure 17 Circuit proposals for over-temperature protection

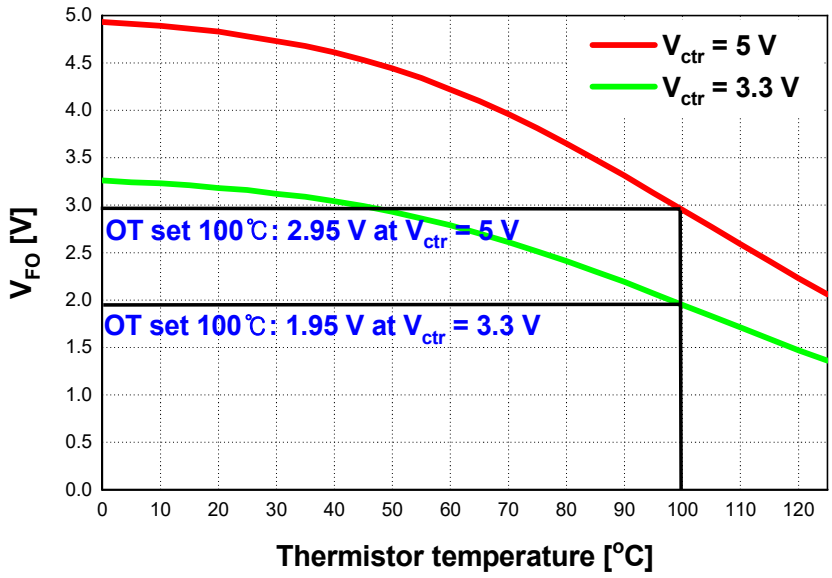


Figure 18 Voltage of V_{FO} pin according to thermistor temperature

6 Bootstrap circuit

6.1 Bootstrap circuit operation

The V_{BS} voltage, which is the voltage difference between $V_{B\,(U,V,W)}$ and $V_{S\,(U,V,W)}$, provides the supply to the IC within the CIPOS™ Mini. This supply voltage must be in the range of 13.0~17.5 V to ensure that the IC can fully drive the high-side IGBT. The CIPOS™ Mini includes an undervoltage detection function for the V_{BS} to ensure that the IC does not drive the high-side IGBT if the V_{BS} voltage drops below a specified voltage (refer to the datasheet). This function prevents the IGBT from operating with a high power dissipation. Please note that the UVLO function of any high-side section acts only on the triggered channel without any feedback to the control level.

There are a number of ways in which the V_{BS} floating supply can be generated. One of them is the bootstrap method described here. This method has the advantage of being simple and cheap. However, the duty cycle and on-time are limited by the requirement to refresh the charge in the bootstrap capacitor. Figure 19 shows the bootstrap supply which is formed by a combination of diode, resistor and capacitor, and the current path of the bootstrap circuit. When V_S is pulled down to ground (e.g. through the low-side or the load), the bootstrap capacitor (C_{BS}) is charged by the bootstrap diode (D_{BS}) and the resistor (R_{BS}) from the V_{DD} supply.

6.2 Internal bootstrap functionality characteristics

CIPOS™ Mini includes bootstrap functionality in the internal driver IC, which consist of three diodes and three resistors, as shown in Figure 3. A typical value of the internal bootstrap resistor is 37 Ω at room temperature. For more information, please refer to Table 16.

V_{DD} of 16 V is recommended when only the integrated bootstrap circuitry is used.

Table 16 Electric characteristics of internal bootstrap parameters

Description	Condition	Symbol	Min.	Typ.	Max.	Unit
Repetitive peak reverse voltage		V_{RRM}	600	-	-	V
Bootstrap diode forward current between V_{DD} and V_B	V_F = 4 V	I_{F_BSD}		54		mA
Bootstrap diode resistance	V_{F1} = 4 V, V_{F2} = 5 V	R_{BSD}	-	37	-	Ω
Bootstrap diode forward voltage between V_{DD} and V_B	I_F = 0.3 mA	V_{F_BSD}	-	1.0	-	V

If it is necessary to reduce the bootstrap resistance, an external bootstrap circuitry is recommended. As an example, when 39 Ω resistor and 1N4937 diode are connected externally to the CIPOS™ Mini, the bootstrap resistance will be around 23 Ω, as shown in Table 17.

Table 17 Bootstrap resistance with external bootstrap circuitry (39 Ω and 1N4937)

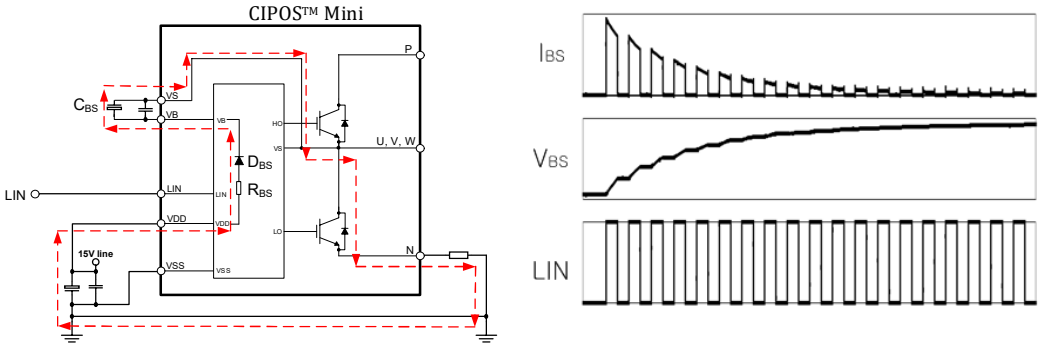
Description	Condition	Symbol	Min.	Typ.	Max.	Unit
Bootstrap resistance	T_J = 25°C T_J = 125°C	R_{BS}	-	22.9 26.5	-	Ω

6.3 Initial charging of bootstrap capacitor

Adequate on-time duration of the low-side IGBT is required to fully charge the bootstrap capacitor for initial bootstrap charging. The initial charging time (t_{charge}) can be calculated from the following equation:

$$t_{charge} \geq C_{BS} \times R_{BS} \times \frac{1}{\delta} \times \ln\left(\frac{V_{DD}}{V_{DD} - V_{BS(min)} - V_{FD} - V_{LS}}\right) \quad (6)$$

- V_{FD} = Forward-voltage drop across the bootstrap diode
- $V_{BS(min)}$ = The minimum value of the bootstrap capacitor voltage
- V_{LS} = Voltage drop across the low-side IGBT
- δ = Duty ratio of PWM



(a) Bootstrap circuit (b) Timing chart of initial bootstrap charging

Figure 19 Bootstrap circuit operation and initial charging

6.4 Bootstrap capacitor selection

The bootstrap capacitance can be calculated by:

$$C_{BS} = \frac{I_{leak} \times \Delta t}{\Delta V} \quad (7)$$

Where,

- Δt = maximum on pulse width of high-side IGBT
- ΔV = the allowable discharge voltage of the C_{BS}
- I_{leak} = maximum discharge current of the C_{BS} mainly via the following mechanisms:
  - Gate charge for turning the high-side IGBT on
  - Quiescent current to the high-side circuit in the IC
  - Level-shift charge required by level-shifters in the IC
  - Leakage current in the bootstrap diode
  - C_{BS} capacitor leakage current (ignored for non-electrolytic capacitors)
  - Bootstrap diode reverse recovery charge

In practice, leakage current of 1 mA is recommended as a calculation basis for CIPOS™ Mini. By taking into consideration dispersion and reliability, the capacitance is generally selected to be 2~3 times higher than the calculated one. The C_{BS} is only charged when the high-side IGBT is off and the V_S voltage is pulled down to ground. Therefore, the on-time of the low-side IGBT must be sufficient to ensure that the charge drawn from the C_{BS} capacitor can be fully replenished. Hence, inherently there is a minimum on-time of the low-side IGBT (or off-time of the high-side IGBT).

The bootstrap capacitor should always be placed as close to the pins of the CIPOS™ Mini as possible. At least one low ESR capacitor should be used to provide good local de-coupling. For example, a separate ceramic capacitor close to the CIPOS™ Mini is essential if an electrolytic capacitor is used for the bootstrap capacitor. If the bootstrap capacitor is either a ceramic or tantalum type, it should be adequate for local de-coupling.

6.5 Charging and discharging of the bootstrap capacitor during PWM inverter operation

The bootstrap capacitor C_{BS} charges through the bootstrap diode D_{BS} and resistor R_{BS} according to Figure 19 from the V_{DD} supply when the high-side IGBT is off, and the V_S voltage is pulled down to ground. It discharges when the high-side IGBT or diode are on.

Example 1: Selection of the initial charging time

An example of the calculation of the minimum value of the initial charging time is given with reference to equation (6).

Conditions:

- C_{BS} = 4.7 µF, R_{BS} = 37 Ω, duty ratio (δ) = 0.5, D_{BS} = internal bootstrap diode, V_{DD} = 15 V, V_{FD} = 1.0 V
- $V_{BS\,(min)}$ = 13 V, V_{LS} = 0.1 V

$$t_{charge} \geq 4.7\ \mu F \times 37\ \Omega \times \frac{1}{0.5} \times \ln\left(\frac{15\ V}{15\ V - 13\ V - 1\ V - 0.1\ V}\right) \cong 0.98\ ms$$

In order to ensure safety, it is recommended that the charging time must be at least three times longer than the calculated value.

Example 2: The minimum value of the bootstrap capacitor

Conditions:

- ΔV = 0.1 V, I_{leak} = 1 mA

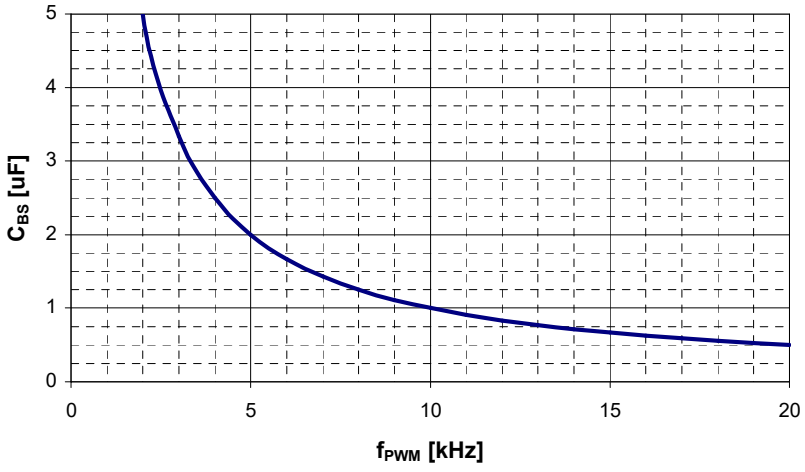


Figure 20 Bootstrap capacitance as a function of the switching frequency

Figure 20 shows the curve corresponding to equation (7) for a continuous sinusoidal modulation, if the voltage ripple ΔV_{BS} is 0.1 V. The recommended bootstrap capacitance for a continuous sinusoidal modulation method is therefore in the range of up to 4.7 µF for most switching frequencies. In other PWM cases such as discontinuous sinusoidal modulation, the t_{charge} must be set at the longest period of the low-side IGBT off. Note that this result is only an example. It is recommended that the system design considers the actual control pattern and lifetime of the components used.

7 Single-phase boost PFC

7.1 Basic introduction

The PFC section of the IM564 series consists of a MOSFET and a diode. 600 V CoolMOS™ MOSFET and 650 V rapid-switching, emitter-controlled diode are selected to deliver lower switching loss and better ruggedness. On the other hand, the PFC section of this IPM does not include the gate driver. This requires more consideration for driving the PFC MOSFET than the 3-phase inverter section.

7.2 General application example

Figure 21 shows a general application example for the PFC section of the CIPOS™ Mini PFC-integrated IPM.

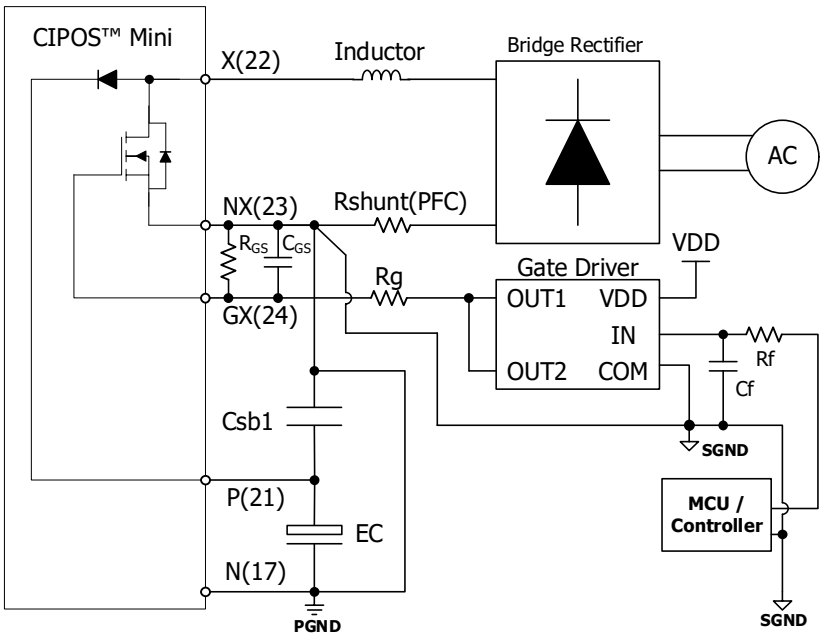


Figure 21 Application example

7.2.1 Gate driver IC

In order to drive the PFC MOSFET, we strongly recommend using a gate driver IC such as 1ED44175N01B or IRS44273L which is a single low-side driver IC. Features of each gate driver IC are as follows:

1ED44175N01B

- CMOS Schmitt-triggered input
- Undervoltage lockout
- Overcurrent limit with minus voltage input
- Enable input and fault output with programmable fault clear time
- 3.3 V, 5 V and 15 V input logic compatible
- 2.6 A sinking / sourcing current (typical)
- 19 ns turn-on/off propagation delay (typical)

IRS44273L

- CMOS Schmitt-triggered input
- Undervoltage lockout
- 3.3 V logic compatible
- 1.5 A sinking / sourcing current (typical)
- 50 ns turn-on/off propagation delay (typical)

7.2.2 Gate resistor selection

For the gate resistance and capacitance for PFC MOSFET, we suggest R_G = 5.1 Ω, C_{GS} = 4.7 nF as shown in Table 18 to have stable operation. However, it can be changed depending on the user's conditions.

Table 18 Switching characteristics at recommended gate drive parameters (V_{DC} = 400 V, V_{GS} = 15 V, I_D = 20 A, T_J = 25°C)

Product	R_G [Ω]	C_{GE} [nF]	E_{ON} [µJ]	On dv/dt [kV/µs]	On di/dt [A/µs]	E_{OFF} [µJ]	Off dv/dt [kV/µs]	Off di/dt [A/µs]
IM564-X6D	5.1	4.7	310	21.4	607	110	75.9	960
IM564-X6DS								

8 Thermal system design

8.1 Introduction

The thermal design of a system is a key issue of CIPOS™ Mini PFC-integrated IPM in electronic systems such as drives. In order to avoid overheating and / or to increase reliability, two design criteria are of importance:

- Low power losses
- Low thermal resistance from junction to ambient

The first criterion is already fulfilled when choosing the CIPOS™ Mini family as the IPM for the application. To get the most out of the system, a proper heat sink choice is necessary. A good thermal design either allows the user to maximize power or to increase the reliability of the system (by reducing the maximum temperature). This application note will give a short introduction to power losses and heat sink, helping to understand the mode of operation and to find the right heat sink for a specific application.

For the thermal design, one needs:

- The maximum power losses $P_{sw,i}$ of each power switch
- The maximum junction temperature $T_{J,max}$ of the power semiconductors
- The junction-to-ambient transient thermal response $Z_{th,J-A}$. For stationary considerations, the static thermal resistance $R_{th,J-A}$ is sufficient. This thermal resistance comprises the junction-to-case thermal resistance $R_{th,J-C}$ as provided in datasheets, the case-to-heat sink thermal resistance $R_{th,C-HS}$ accounting for the heat flow through the thermal interface material between heat sink and the power module and the heat sink-to-ambient thermal resistance $R_{th,HS-A}$. Each thermal resistance can be extended to its corresponding thermal impedance by adding the thermal capacitances.
- The maximum allowable ambient temperature $T_{A,max}$

Furthermore, all heat flow paths need to be identified. Figure 22 presents a typical simplified equivalent circuit for the thermal network of CIPOS™ Mini PFC-integrated IPM. This circuit is simplified as it omits thermal capacitances and typically negligible heat paths such as the heat transfer from the module surface directly to the ambient via convection and radiation.

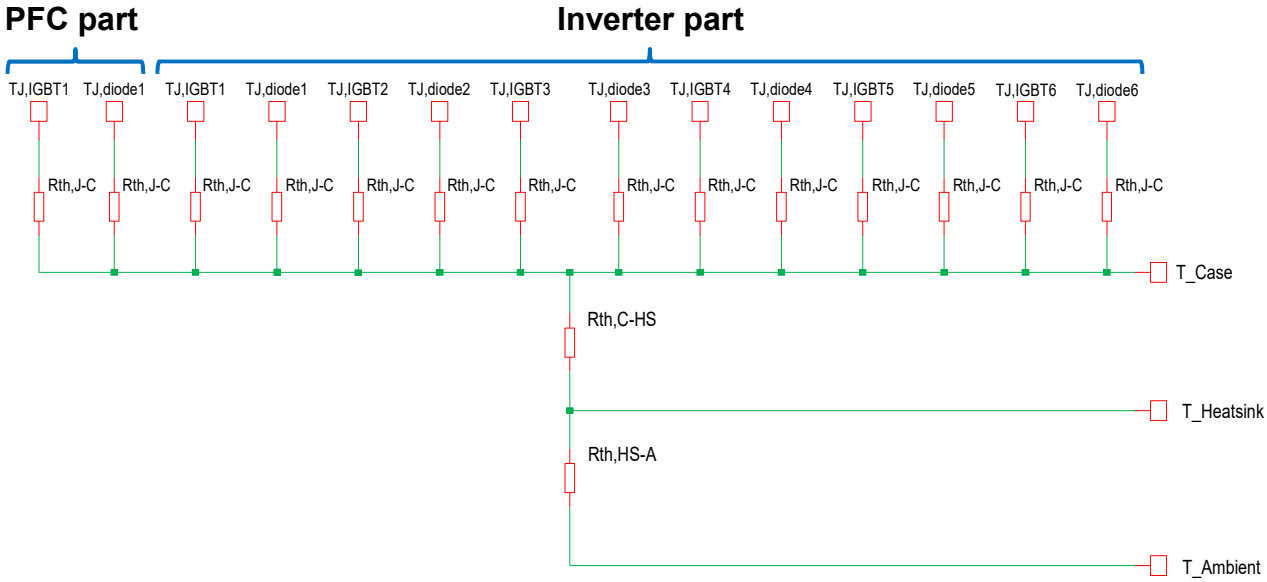


Figure 22 Simplified thermal equivalent circuit

8.2 Power loss (inverter section)

The power losses of the inverter section in the CIPOS™ Mini PFC-integrated IPM are composed of conduction and switching losses in the IGBTs and diodes. The loss during the turn-off steady state can be ignored because it is very low and has little effect on increasing the temperature in the device. The conduction loss depends on the DC electrical characteristics of the device, i.e. saturation voltage. Therefore, it is a function of the conduction current and the device's junction temperature. On the other hand, the switching loss is determined by the dynamic characteristics like turn-on/off time and over-voltage/current. Hence, in order to obtain the accurate switching loss, the DC-link voltage of the system, the applied switching frequency and the power circuit layout in addition to the current and temperature should be considered.

In this chapter, based on a PWM-inverter system for motor-control applications, detailed equations are shown to calculate both losses of the CIPOS™ Mini for a 3-phase continuous sinusoidal PWM. For other cases like 3-phase discontinuous PWMs, please refer to [8].

8.2.1 Conduction losses

The typical characteristics of forward-drop voltage are approximated by the following linear equation for the IGBT and the diode, respectively. Figure 23 shows an example of linear approximation of typical output characteristics.

$$V_{IGBT} = V_I + R_I \cdot i$$
$$V_{DIODE} = V_D + R_D \cdot i \qquad (8)$$

- V_I = Threshold voltage of IGBT
- V_D = Threshold voltage of diode
- R_I = on-state slope resistance of IGBT
- R_D = on-state slope resistance of diode

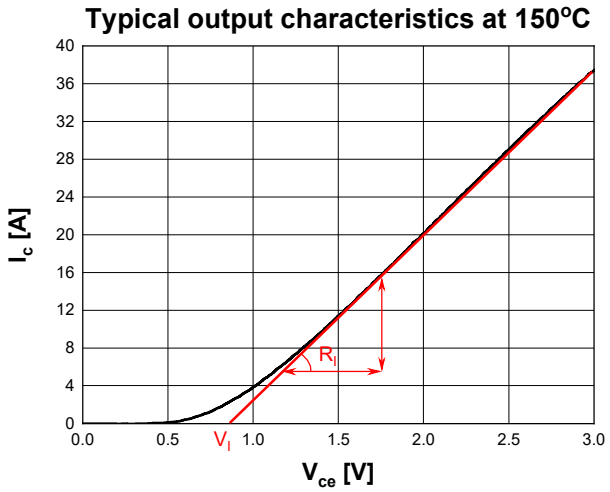


Figure 23 Linear approximation of output characteristics

Assuming that the switching frequency is high, the output current of the PWM inverter can be assumed to be sinusoidal. That is,

$$i = I_{peak} \cos(\theta - \varphi) \qquad (9)$$

Where, φ is the phase-angle difference between output voltage and current. Using equations (8) and (9), the conduction loss of one IGBT and its freewheeling diode can be obtained as follows:

$$P_{con.I} = \frac{1}{2\pi}\int_0^{\pi} \xi(V_{IGBT} \times i)d\theta = \frac{I_{peak}}{2\pi}V_I + \frac{I_{peak}}{8}V_I MI\cos\varphi + \frac{I_{peak}^{\ 2}}{8}R_I + \frac{I_{peak}^{\ 2}}{3\pi}R_I MI\cos\varphi \quad (10)$$

$$P_{con.D} = \frac{1}{2\pi}\int_0^{\pi} (1-\xi)(V_{DIODE} \times i)d\theta = \frac{I_{peak}}{2\pi}V_D - \frac{I_{peak}}{8}V_D MI\cos\varphi + \frac{I_{peak}^{\ 2}}{8}R_D - \frac{I_{peak}^{\ 2}}{3\pi}R_D MI\cos\varphi \quad (11)$$

$$P_{con} = P_{con.I} + P_{con.D} \quad (12)$$

Where ξ is the duty cycle in the given PWM method.

$$\xi = \frac{1 + MI\cos\theta}{2} \quad (13)$$

Where, MI is the PWM modulation index (MI, defined as the peak phase voltage divided by the half of the DC-link voltage).

It should be noted that the total inverter conduction losses are six times that of the P_{con}.

8.2.2 Switching losses

Switching losses vary according to the device technologies, the working voltage/current and the operating temperature/frequency. However, the turn-on/off loss energy (Joule) can be measured indirectly during tests by multiplying the current and voltage and integrating over time, under a given circumstance. Therefore the linear dependency of the switching energy loss on the switched current is expressed during one switching period as follows.

$$\text{Switching energy loss} = (E_I + E_D) \times i\ [J] \quad (14)$$

$$E_I = E_{I.ON} + E_{I.OFF} \quad (15)$$

$$E_D = E_{D.ON} + E_{D.OFF} \quad (16)$$

Where, E_I is the switching loss energy of the IGBT and E_D is for the diode. E_I and E_D can be considered a constant approximately.

As mentioned in the equation (9), the output current can be considered a sinusoidal waveform and the switching loss occurs every PWM period for the continuous PWM schemes. Therefore, depending on the switching frequency f_{sw}, the switching loss of one device is the following equation (17).

$$P_{sw} = \frac{1}{2\pi}\int_0^{\pi} (E_I + E_D)\ i\ f_{sw} d\varphi = \frac{(E_I + E_D) f_{sw} I_{peak}}{\pi} \quad (17)$$

Where, E_I is a unique constant of IGBT related to the switching energy, and different IGBT have different E_I values. E_D is the constant for the diode. Those should be derived by measurements done in experiments. From the equation (17), it should be noted that the switching losses are a linear function of current, and directly proportional to the switching frequency.

8.3 Power loss (PFC section)

PFC shapes the input current of the power supply to be synchronized with the mains voltage to maximize the real power drawn from the mains. In a perfect PFC circuit, the input current follows the input voltage as a pure resistor, without any input current harmonics. In order to design properly, we need to consider several factors. However, in this chapter, we introduce the equation for power loss estimation of MOSFETs and diodes. For

other design information such as for bridge rectifier, gate drive circuit, boost inductor, AC line current filter, and etc., please refer to [9]

8.3.1 Conduction losses

Following is the theory for a simplified power loss calculation.

For simplicity purposes, input waveforms are full periodic sinusoidal signals:

$V_{in}(t) = V_{in,peak} \times sin(\omega t)$

The first half wave (T/2) current for the controlled and uncontrolled switch:

$I_{in}(t) = I_{in} \times sin(\omega t)$

$I_{MOSFET}(t) = \mathrm{D}(t) * I_{in}(t)$

$I_{Diode}(t) = (1 - \mathrm{D}(t)) * I_{in}(t)$

For MOSFET on duty in case of contiuous conduction mode operation:

$$D(t) = 1 - \frac{V_{in}(t)}{V_{out}}$$

The average conduction loss of the MOSFET for the first half wave is:

$$P_{cond,\mathrm{MOSFET}} = \frac{2}{T}\int_0^{\frac{T}{2}} I_{in}(t)^2 \times R_{DS(on)}(I_{in}(t)) \times D(t)dt$$

For the diode, linear approximation is used as in the inverter section. The average conduction loss for the boost diode is:

$$P_{cond,diode} = \frac{V_{in,peak}}{V_{out}} * (V_D * I_{in} * \frac{1}{\sqrt{2}} + R_D * I_{in}^2 * \frac{8}{3 * \pi})$$

8.3.2 Switching losses

The influence of the diode for the switching-on losses of the MOSFET makes it necessary to characterize the MOSFET and diode pair together.

$$P_{swi,\mathrm{MOSFET}} = f_{SW} * \frac{2}{T} * \int_0^{\frac{T}{2}} E_{off}\big(I_{MOSFET}(t)\big) + E_{on}\big(I_{MOSFET}(t)\big)dt$$

Assuming linear switching characteristics, it is possible to describe the switching characteristics with four parameters ($E_{off,0}$, $E_{off,n}$, $E_{on,0}$, $E_{on,n}$) and use them for calculation of the switching losses:

$$E_{off}(I_{MOSFET}) = E_{off,0} + \frac{E_{off,n} - E_{off,0}}{I_n} * I_{MOSFET}$$

$$E_{on}(I_{IGBT}) = E_{on,0} + \frac{E_{on,n} - E_{on,0}}{I_n} * I_{MOSFET}$$

With I_n and V_n being the nominal current and output voltage where switching losses were measured, and f_{SW} is a constant switching frequency:

$$P_{swi,\mathrm{MOSFET}} = \frac{V_{out}}{V_n} * f_{SW} * \frac{2}{T} * \int_0^{\frac{T}{2}} E_{off,0} + E_{on,0} + \frac{(E_{off,n} - E_{off,n} + E_{on,n} - E_{on,0})}{I_n} * I_{MOSFET}(t)dt$$

The switching losses are calculated to:

$$P_{swi,\mathrm{MOSFET}} = \frac{V_{out}}{V_n} * f_{SW} * (E_{off,0} + E_{on,0} + \frac{I_{in}}{I_n} * \sqrt{2} * \frac{2}{\pi} * (E_{off,n} - E_{on,0} + E_{on,n} - E_{on,0})$$

The same for the diode:

$$P_{swi,Diode} = \frac{V_{out}}{V_n} * f_{SW} * (E_{rec,0} + \frac{I_{in}}{I_n} * \sqrt{2} * \frac{2}{\pi} * (E_{rec,n} - E_{rec,0}))$$

8.4 Thermal impedance

In practical operation, the power loss P_D is cyclic, and therefore the transient impedance needs to be considered. The thermal impedance is typically represented by a RC equivalent circuit as shown in Figure 24. For pulsed power loss, the thermal capacitance effect delays the rise in junction temperature, and thus permits a heavier loading of the CIPOS™ Mini. Figure 25 and Figure 26 show junction-to-case thermal impedance curves of power devices. The thermal resistance goes into saturation in about 10 seconds.

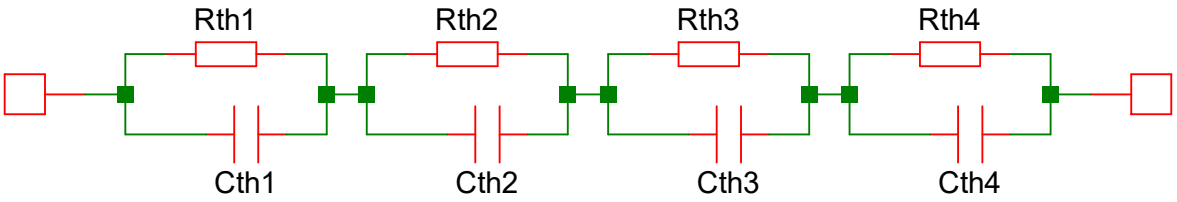


Figure 24 Thermal impedance RC equivalent circuit

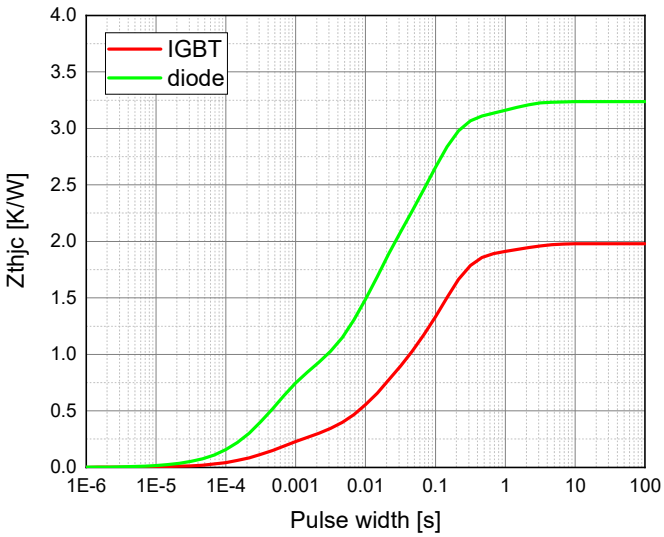


Figure 25 Thermal impedance curves (IM564-X6D, inverter part)

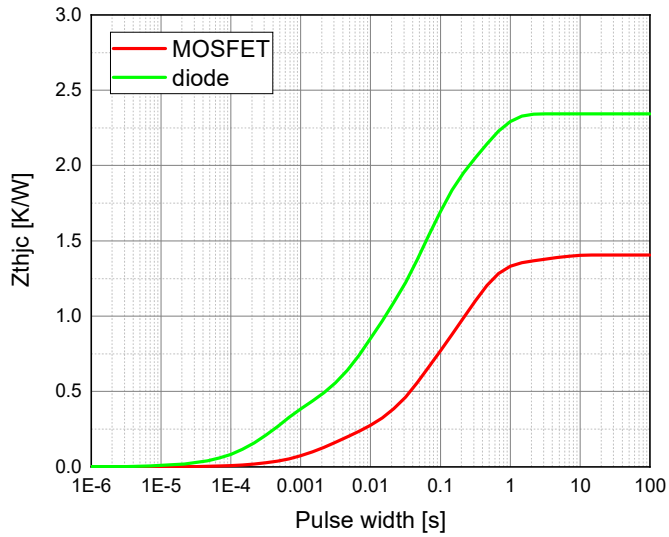


Figure 26 Thermal impedance curves (IM564-X6D, PFC part)

8.5 Temperature-rise consideration and calculation example

The on-line simulation tool for PFC-integrated IPMs allows for calculating power losses and estimated temperature. Figure 27 shows an example with V_{PN} = 360 V, V_{DD} = 15 V, $f_{SW.inv}$ = 5 kHz, $f_{SW.PFC}$ = 40 kHz, V_{IN} = 220 V, V_{motor} = 176 V, I_{motor} = 12.3 A, T_C = 100°C.

PFC + Inverter IPM

	Part Name	Total Losses	Input Power	Output Power	Avg. Case Temp.
IPM	IM564-X6D	100.74 W	3.100 kW	3.000 kW	100.0 °C

PFC Losses and Junction Temperature

	Part Name	Switching Losses	Conduction Losses	Total Losses	Avg. Junction Temp.	Max Junction Temp.
PFC Switch	IM564-X6D	10.86 W	6.75 W	17.61 W	124.8 °C	125.8 °C
PFC Diode	IM564-X6D	3.51 W	11.02 W	14.53 W	134.0 °C	139.2 °C
PFC	IM564-X6D			32.13 W		

Inverter Losses and Junction Temperatures

	Part Name	Switching Losses	Conduction Losses	Total Losses	Efficiency	Avg. Junction Temp.	Max Junction Temp.
Inverter Switches	IM564-X6D	9.55 W	42.93 W	52.48 W		117.3 °C	124.0 °C
Inverter Diodes	IM564-X6D	1.19 W	14.94 W	16.13 W		108.7 °C	115.6 °C
Inverter	IM564-X6D			68.61 W	97.71 %		

Figure 27 Power losses and junction temperature at given conditions

8.6 Heat sink selection guide

8.6.1 Required heat sink performance

If the power losses $P_{sw,i}$, $R_{th,J\text{-}C}$ and the maximum ambient temperature are known, the required thermal resistance of the heat sink and the thermal interface material can be calculated according to Figure 24 from,

$$T_{J,max} = T_{A,max} + \sum_i P_{sw,i} \cdot R_{th,HS-A} + \sum_i P_{sw,i} \cdot R_{th,C-HS} + Max(P_{sw,i} \cdot R_{th,JC,i}) \quad (18)$$

For three-phase bridges, one can simply assume that all power switches dissipate the same power, and all have the same $R_{th,J\text{-}C}$. This leads to the required thermal resistance from case to ambient.

$$R_{th,C-A} = R_{th,C-HS} + R_{th,HS-A} = \frac{T_{J,max} - P_{sw} \cdot R_{th,JC} - T_{A,max}}{\sum P_{sw}} \quad (19)$$

As an example, the power switches of an air conditioner dissipate 8.75 W maximum each; the maximum ambient temperature is 50°C, the maximum junction temperature is 150°C and $R_{th,JC}$ is 2 K/W. It results in,

$$R_{th,C-A} \leq \frac{150^oC - 8.75\ W \times 2\ K/W - 50^oC}{6 \times 8.75\ W} = 1.57\ \text{K/W}$$

If the heat sink temperature is limited to 100°C, an even lower thermal resistance is required:

$$R_{th,C-A} \leq \frac{100^oC - 50^oC}{6 \times 8.75\ W} = 0.95\ K/W$$

Smaller heat sinks with higher thermal resistances may be acceptable if the maximum power is only required for a short time (times below the time constant of the thermal resistance and the thermal capacitance). However, this requires a detailed analysis of the transient power and temperature profiles. The larger the heat sink and the larger its thermal capacitance, the longer it takes to heat up the heat sink.

8.6.2 Heat sink characteristics

Heat sinks are characterized by three parameters:

- Heat transfer from the power source to heat sink
- Heat transfer within the heat sink (to all the surfaces of the heat sink)
- Heat transfer from heat sink surfaces to ambient

8.6.2.1 Heat transfer from heat source to heat sink

In the case of IPM products, the heat source is the junction of power devices as shown in Figure 22. The thermal path from junction to case is determined when the appropriate IPM product is selected for the target application. There are two factors which need to be considered in order to provide a good thermal contact between case and heat sink:

- **Flatness of the contact area**
  - Due to the unevenness of surfaces, a thermal interface material needs to be applied between case and heat sink. However, such materials have a rather low thermal conductivity (<10 K/W). Hence these materials should be as thin as possible. On the other hand, they need to fill out the space between case and heat sink. Therefore, the heat sink should be as even as possible. In addition, the particle size of the interface material must fit to the roughness of the module and the heat sink surfaces. Particles that are too large will unnecessarily increase the thickness of the interface layer, and hence will increase the

thermal resistance. Particles that are too small will not provide a good contact between the two surfaces, and will lead to a higher thermal resistance as well.

- **Mounting pressure**
  - The higher the mounting pressure, the better the interface material disperses, and excessive interface material squeezes out resulting in a thinner interface layer with a lower thermal resistance. Please refer to Table 20 for the mounting torque guideline.

8.6.2.2 Heat transfer within the heat sink

The heat transfer within the heat sink is mainly determined by:

- **Heat sink material**
  - The material needs to be a good thermal conductor. Most heat sinks are made of aluminum (λ ≈ 200 W/ (m*K)). Copper is heavier and more expensive but also nearly twice as efficient (λ ≈ 400 W/ (m*K)).
- **Fin thickness**
  - If the fins are too thin, the thermal resistance from heat source to fin is too high and the efficiency of the fin decreases. Hence it does not make sense to make the fins as thin as possible in order to have more fins and therefore to increase the surface area.

8.6.2.3 Heat transfer from heat sink surface to ambient

The heat transfers to the ambient mainly by convection. The corresponding thermal resistance is defined as

$$R_{th,conv} = \frac{1}{\alpha \cdot A} \qquad (20)$$

Where α is the heat transfer coefficient and A is the surface area.

Hence there are two important parameters:

- **Surface area:** Heat sinks require a huge surface area in order to easily transfer the heat to the ambient. However, as the heat source is assumed to be concentrated at one point and not uniformly distributed, the total thermal resistance of a heat sink does not change linearly with length. Also, increasing the surface area by increasing the number of fins does not necessarily reduce the thermal resistance as discussed in section 8.6.2.2.
- **Heat transfer coefficient (aerodynamics):** This coefficient depends heavily on the air flow velocity as shown in Figure 28. If there is no externally induced flow, one speaks of natural convection, otherwise it is forced convection. Heat sinks with very small fin spacing do not allow a good air flow. If a fan is used, the fin gap may be lower than with natural convection, as the fan forces the air through the space between the fins.

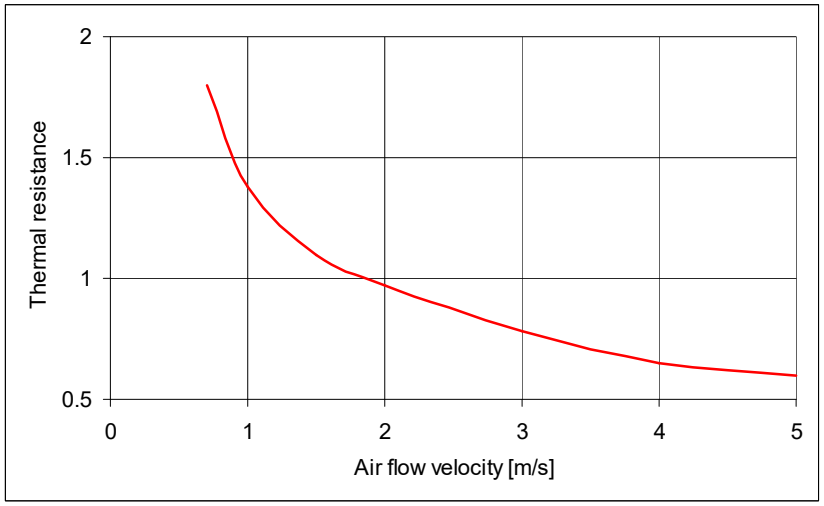


Figure 28 Thermal resistance as a function of the air flow velocity

Furthermore, in the case of natural convection, the heat sink efficiency depends on the temperature difference of the heat sink and ambient (i.e. on the dissipated power). Some manufacturers, like Aavid Thermalloy, provide a correction table which allows the user to calculate the thermal resistance depending on the temperature difference. Figure 29 shows the heat sink efficiency degradation for natural convection as provided in [10]. Please note that the thermal resistance is 25% higher at 30 K than at 75 K.

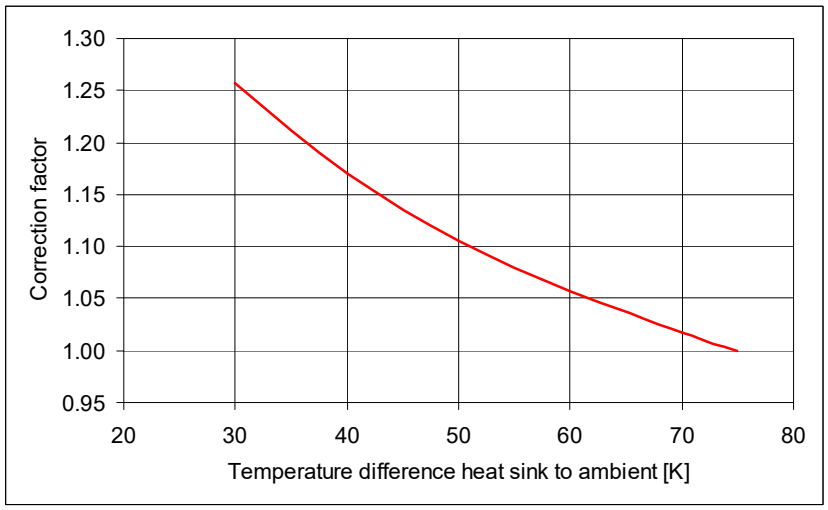


Figure 29 Correction factors for temperature

The positioning of the heat sink plays also an important role for aerodynamics. In the case of natural convection the best mounting attitude is with vertical fins as the heated air tends to move upwards due to buoyancy. Furthermore, one should make sure that there are no significant obstructions impeding the air flow.

Radiation occurs as well supporting the heat transfer from heat sink to ambient. In order to increase radiated heat one can use anodized heat sinks with a black surface. However, this decreases the thermal resistance of the heat sink only by a few percent in the case of natural convection. Radiated heat is negligible with forced convection. Hence, blank heat sinks can be used if a fan is not used with the heat sink.

The discussions in this section clearly show that there cannot be one single thermal resistance value assigned to a certain heat sink.

8.6.3 Selecting a heat sink

Unfortunately, there are no straightforward formulas for selecting heat sinks. Finding a sufficient heat sink will include an iterative process of choosing and testing heat sinks. In order to get a first rough estimation of the required volume of the heat sink, one can start with estimated volumetric thermal resistances as given in Table 19 (taken from [11]). This table provides only an initial overview, as the actual resistance may vary depending on many parameters like actual dimensions, type, orientation, etc.

Table 19 Volumetric thermal resistance

Flow conditions [m/s]	Volumetric resistance [cm^3 °C/W]
Natural convection	500 ~ 800
1.0	150 ~ 250
2.5	80 ~ 150
5.0	50 ~ 80

One can roughly assume that the volume of a heat sink needs to be quadrupled in order to half its thermal resistance. This gives an idea of whether natural convection is sufficient for the available space, or whether forced convection is required.

In order to get an optimized heat sink for a given application, one needs to contact heat sink manufacturers or consultants. A further overview and references can be found in [11].

When contacting heat sink manufacturers in order to find a suitable heat sink, please find out under which conditions the given thermal resistance values are valid. They might be given either for a point source or for a heat source which is evenly distributed over the entire base area of the heat sink. Also make sure that the fin spacing is optimized for the corresponding airflow conditions.

9 Heat sink mounting and handling guidelines

9.1 Heat sink mounting

9.1.1 General guidelines

An adequate heat sinking capability of the CIPOS™ Mini is only achievable if it is suitably mounted. This is the fundamental requirement to meet the electrical and thermal performance of the module. The following general points should be observed when mounting CIPOS™ Mini on a heat sink. Verify the following points related to the heat sink:

a) There must be no burrs on aluminum or copper heat sinks.
b) Screw holes must be countersunk.
c) There must be no unevenness or scratches in the heat sink.
d) The surface of the module must be completely in contact with the heat sink.
e) There must be no oxidation nor stain or burrs on the heat sink surface.

To improve the thermal conductivity, apply silicone grease to the contact surface between the CIPOS™ Mini and heat sink. Spread a homogenous layer of silicone grease with a thickness of 100 µm over the CIPOS™ Mini substrate surface. Non-planar surfaces of the heat sink may require a thicker layer of thermal grease. Please refer here to the specifications of the heat sink manufacturer. It is important to note that the heat sink covers the complete backside of the module. There may be different functional behavior if there is a portion of the back side of the module is not in contact with the heat sink.

To prevent a loss of heat dissipation effect due to warping of the substrate, tighten the mounting screws gradually and sequentially while maintaining a left/right balance in pressure applied.

It must be assured by the design of the application PCB that the plane of the back side of the module and that of the heat sink are parallel to achieve a minimal tension of the package and an optimal contact of the module with the heat sink. Please refer to the mechanical specifications of the module given in the datasheets.

It is the basics of good engineering to verify the function and thermal conditions by means of detailed measurements. It is best to use a final application inverter system, which is assembled with the final production process. This helps to achieve high-quality applications.

9.1.1.1 Recommended tightening torque

As shown in Table 20, the tightening torque of M3 screws is specified for a minimum 0.49 N·m and maximum 0.78 N·m. The screw holes must be centered to the screw openings of the mold compound, so that the screws do not come into contact with the mold compound. If an insulating sheet is used, use a sheet larger than the CIPOS™ Mini, which should be aligned accurately when attached. It is important to ensure that no air is enclosed by the insulating sheet. Generally speaking, insulating sheets are used in the following cases:

- When the ability to withstand primary and secondary voltages is required to achieve required safety standards against a hazardous situation.
- When the CIPOS™ Mini has to be insulated from the heat sink.
- When measuring the module, to reduce radiated noise or eliminate other signal-related problems.

Table 20 Mechanical characteristics and ratings

Item	Condition	Package type	Limits			Unit
			Min.	Typ.	Max.	
Mounting torque	Mounting screw : M3	DCB	0.49	-	0.78	N·m
Device flatness	(Note Figure 30)		-50	-	+100	µm
Heat sink flatness	(Note Figure 31)		-50	-	+100	µm
Weight		DCB	-	6.83	-	g

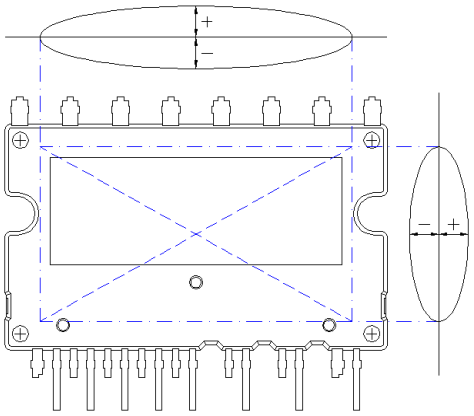


Figure 30 Device flatness measurement position

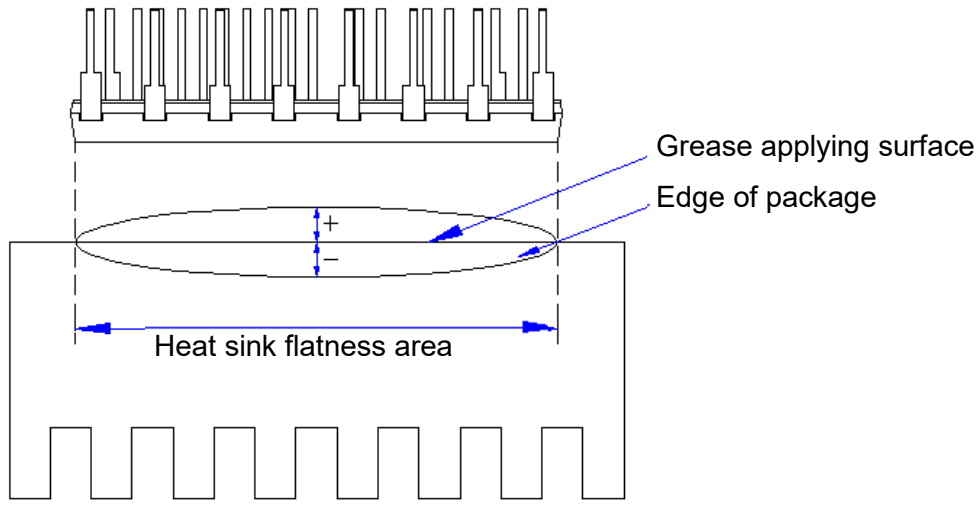


Figure 31 Heat sink flatness measurement position

9.1.1.2 Screw tightening to heat sink

The tightening of the screws is the main process of attaching the module to the heat sink. It is assumed that an interface pad is attached to the heat sink surface, which extends to the edge of the module, and which is aligned to the fixing holes. It is recommended that M3 fixing screws be used in conjunction with a spring washer and a plain washer. The spring washer must be assembled between the plain washer and the screw head. The screw torque must be monitored by the fixing tool.

Tightening process:

- Align module with the fixing holes
- Insert screw A with washers to touch only position (pre-screwing)
- Insert screw B with washers (pre-screwing)
- Tighten screw A to final torque
- Tighten screw B to final torque

Note: The pre-screwing torque is set to 20~30% of maximum torque rating.

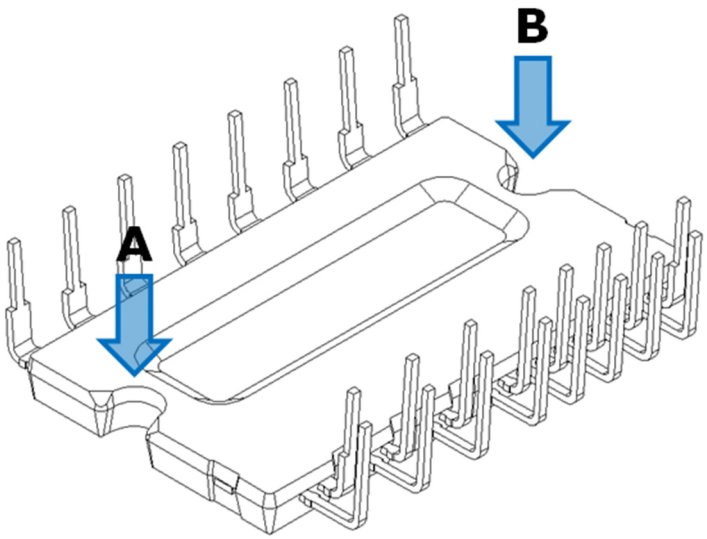


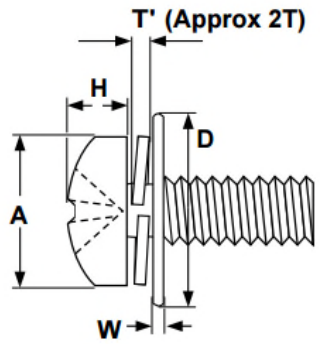
Figure 32 Recommended screw-tightening process: pre-screwing A → B, final screwing A → B

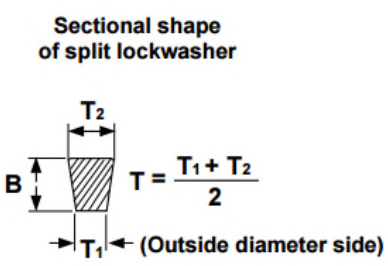
9.1.1.3 Mounting screw

M3 SEMS screw (JIS B1256/JIS B1188) is recommended as shown in Table 21.

Table 21 Recommended screw specification (typical)

Screw dimensions				Flat washer		Spring washer	
Size	Thread pitch	A Head diameter	H Head height	D Outer diameter	W Thickness	D1 Outside diameter	B x T
M3	0.5	5.2	2.0	7.8	0.58	5	1.1 x 0.7





9.1.2 Recommended heat sink shape and system mechanical structure

A shock or vibration through the PCB or heat sink might cause the crack of the package mounted on the heat sink. To avoid a broken or cracked package, and for the PCB or heat sink to endure shock or vibration, a heat sink shape is recommended as shown in Figure 33. The heat sink needs to be fixed to the PCB with screws or eyelets. In the mass production stage, the process sequence for system assembly in terms of device soldering on PCB, heat sink mounting and casing etc., should be taken into account to avoid mechanical stress on the device pins, package mold compound, heat sink and system enclosure etc.

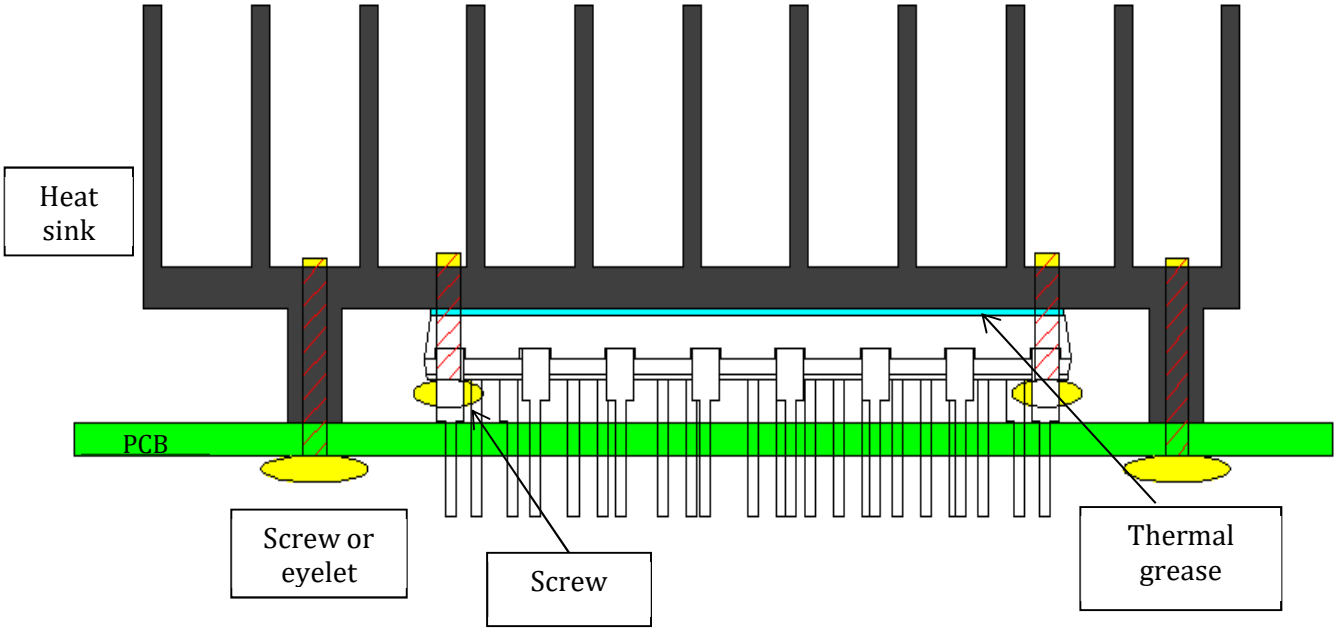


Figure 33 Recommended heat sink shape

9.2 Handling guidelines

When installing a module to a heat sink, excessive uneven tightening force might apply stress to inside chips, which will lead to a broken or degradation of the device. An example of recommended fastening order is shown in Figure 32.

- Do not over torque when mounting the screws. Excessive mounting torque may cause damage to module hole as well as damage to the screw and heat sink.
- Avoid one-side tightening stress. Uneven mounting can cause the module hole to be damaged.

To get effective heat dissipation, it is necessary to enlarge the contact area as much as possible, which minimizes the contact thermal resistance.

Properly apply thermal interface material over the contact surface between the module and the heat sink, which is also useful for preventing the contact surface from corrosion. Furthermore, the thermal interface material should be of stable quality and long-term endurance within a wide operating temperature range. Use a torque wrench to tighten to the specified torque rating. Exceeding the maximum torque limitation might cause a module to be damaged or degraded. Pay attention not to have any dirt remaining on the contact surface between the module and the heat sink. All equipment, which is used to handle or mount CIPOS™ Mini IPMs must comply with the relevant ESD standards. This includes e.g. transportation, storage and assembly. The module itself is an ESD-sensitive device. It may therefore be damaged in case of ESD shocks.

Do not shake or handle by gripping the heat sink only. In particular do not put stress on the PCB by gripping the heat sink alone. That might cause the package to crack or a break.

9.3 Storage guidelines

9.3.1 Recommended storage conditions

Temperature: 5 ~ 35℃

Relative humidity: 45 ~ 75%

- Avoid leaving the CIPOS™ Mini family exposed to moisture or direct sunlight. In particular, be careful during periods of rain or snow.
- Use storage areas where there is minimal temperature fluctuation.

Rapid temperature changes can cause moisture condensation on the stored CIPOS™ Mini, resulting in lead oxidation or corrosion, and lead to degraded solderability.

- Do not allow the CIPOS™ Mini family to be exposed to corrosive gasses or dusty conditions.
- Do not allow excessive external forces or loads to be applied to the CIPOS™ Mini family while they are in storage.

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Revision history

Document version	Date of release	Description of changes
V 1.0	2019-10-25	Initial release

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Edition 2019-10-25

Published by

Infineon Technologies AG

81726 Munich, Germany

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Document reference
AN2019-36

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