TO-247PLUS IGBT discrete device enhances power density in welding machines

Extending the range of use of discrete IGBTs to power levels typically achieved by standard IGBT modules

About this document

Scope and purpose

This document presents an improved solution using discrete IGBTs for power supply converters of welding machines typically using standard IGBT modules. The enhanced performance of the proposed solution is demonstrated with a 400 A, three-phase, full-bridge welding power supply using IKQ75N120CS6 TO-247PLUS devices. The proposed solution increases power density, and enables higher output current using lower current rate discrete devices. Hence, it allows an extension of the application range of discrete IGBTs to power levels typically achieved by standard IGBT modules, reducing the cost of medium-power welding machines.

Intended audience

This document is intended for a technical audience with a minimum knowledge of power electronics and thermal management design.

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1 Introduction

Welding applications are very performance-demanding and cost-intensive, consequently performance and price are key when choosing the right power semiconductor. The typical high power density and switching frequency operation, in addition to the toughest environments, demand high performance and reliability of power semiconductors. This is the case with welding machines in the power range of ≤ 20 kW, where typically 1200 V IGBT power modules are used in the power supply converter. However, newly developed IGBT technologies and discrete packages, along with the characteristic IGBT requirements of the currently used DC/DC network topologies show a very interesting potential for IGBTs optimized for these specific application requirements. Furthermore, unconventional assembly and thermal design methods offer improved designs that increase power density and enable higher output currents with lower current-rated devices.

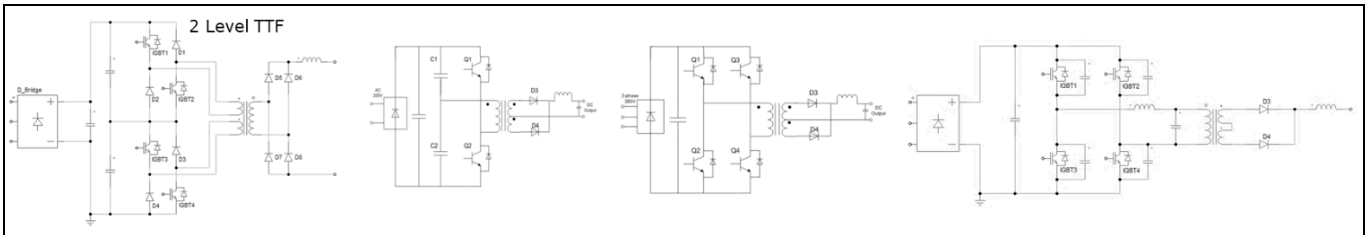
This is the case with the improved solution proposed for welding-machine power supplies based on a known but not often used thermal design concept for increasing heat dissipation, in which discrete IGBTs are directly mounted on the heatsink without any electrical isolation. Hence, a different mechanical design approach needs to be considered for the arrangement of the separated heatsinks with galvanic isolation. For instance, in typical welding machines with an output current of ≥ 250 A, frequently used for light or medium industrial welding tasks in sectors such as the automobile and iron industries as shown in Table 1, the state-of-the-art welding converter designs mainly use IGBT modules such as standard 34 mm modules or even larger packages. However, this unconventional thermal design approach allows an extension of the application range of discrete IGBTs to power levels typically achieved by standard IGBT modules, thus reducing the cost of medium-power welding machines. In particular, the improved performance of Infineon's TO-247PLUS discrete package is excellent for this proposed solution, enhancing the performance and fulfilling the requirements of welding machines.

Table 1 Power semiconductors solutions in the arc welding industry

	Compact/portable welding Output current < 200 A	Light-medium industrial welding Output current ≥ 200 A	Heavy industrial welding Output currents > 400 A
Application industries examples	General fabrication, repair and maintenance	Automobile and iron industries, pipelines	Oil and gas, naval and metallurgical industries
Power semiconductors solution	Mainly discrete devices	Discrete and mainly modules	Modules and discs

1.1 Typical converter topologies in medium-power welding machines

The selection of any specific isolated DC-DC converter topology is based mainly on target parameters such as the arc-welding process and output power requirements. These include output current/voltage, the maximum duty cycle of welding operation, design complexity, system size, weight and finally, cost. Accordingly, the most common DC-DC converter topologies for medium-power welding machines are two transistors forward (TTF), half-bridge (HB), full-bridge (FB), and LLC resonant converter illustrated in Figure 1.



a) Two Transistors Forward b) Half-Bridge c) Full-Bridge d) LLC Resonant

Figure 1 Typical DC-DC converter topologies used in medium-power welding machines

These converters are often controlled by common current-mode PWM controllers, and operate at fully soft switching conditions in the case of the LLC resonant topology, or with zero current switching (ZCS) at turn-on and hard switching at turn-off. This enables high switching frequencies, improved efficiency, increased power density, and lower system cost. For reference, specifics of the typical topologies used in welding machines are explained in [1].

1.2 Discrete solution vs. module solution overview

Inverter arc welding machines using IGBT modules have been used since the 1990s, although IGBT discrete solutions first started to become popular in the early 21st century [2]. Initially, discrete solutions were selected for relatively low power systems below 5 kVA. In comparison, module solutions have always been selected to serve higher power systems exceeding 5 kVA. However, the constant development of advanced IGBT technologies and new packages has allowed the usage of discrete devices on significantly higher power levels, around 25 kVA, and in certain cases, even up to 100 kVA. Furthermore, specific characteristics of the discrete solution, such as higher operating switching frequency (due to lower parasitic inductance), design flexibility, and typically higher operating junction $T_{j\,max}$ result in a more compact size, and reduced weight and cost of the system. In addition, contrary to modules offering few standard current rating levels with a big gap between them, the larger discrete IGBT portfolio with many current ratings enables optimization, prevents oversizing or undersizing of system designs, and facilitates the fulfilment of industry's general requirements for a second supplier. However, discrete solutions are limited, as the parallel connection of several devices can produce a much greater parasitic inductance, which affects performance at higher power levels. Hence, the discrete solution is mostly used currently for power levels up to 50 kVA. When this power level is exceeded, the module design is the most suitable and preferred solution.

Table 2 Discrete solution vs. module solution in welding machines - brief overview

Parameter	Discrete IGBT solution	Module IGBT solution
Cost	Low cost	Expensive
Switching frequency	High	Medium
Output power	Low to medium	Medium to high
Advantages	Design flexibility Reduced stray inductance Mostly 175°C $T_{j\,max}$ Second source easier	Electrically isolated Different configuration availability Usually includes Kelvin emitter pin Better solution at high power level

As Table 2 shows, the module solution offers electrical isolation from the heatsink. In contrast, except for Infineon's unique advanced isolation package devices [4], the discrete solution consists of non-isolated devices, and additional insulation material between package and heatsink is required. However, using insulation material increases the thermal resistance, decreases efficiency, and increases the cost of the system. For this reason, some manufacturers have opted for the unconventional approach of mounting the discrete devices directly on the heatsink without any electrical isolation. This eliminates the need for insulation material and for galvanic isolation via appropriate heatsink and mechanical design.

1.3 TO-247PLUS package improving medium-power welding machines

The TO-247PLUS is a new discrete package family introduced by Infineon, which includes the TO-247PLUS 3-pin and the TO-247PLUS 4-pin with an additional Kelvin emitter connection. This package was developed to accommodate an increased quantity of silicon, and to provide a higher current-carrying capability than the conventional TO-247 package. Furthermore, the new TO-247PLUS package shows improved thermal performance with respect to the TO-247 package. The thermal management is improved with better heat dissipation by lower thermal resistance, which means a smaller heatsink and a lower cost for the cooling infrastructure. For instance, using the same silicon die as in a TO-247 package, customer applications can achieve higher current levels at the same or even lower junction temperature.

The larger lead frame area of the TO-247PLUS package can accommodate larger IGBT chips achieving twice the rated current with integrated full-rated anti-parallel diode. As a result, the TO-247PLUS package allows up to 120 A and 75 A for 600 V/650 V and 1200 V IGBT Co-Pack devices respectively.

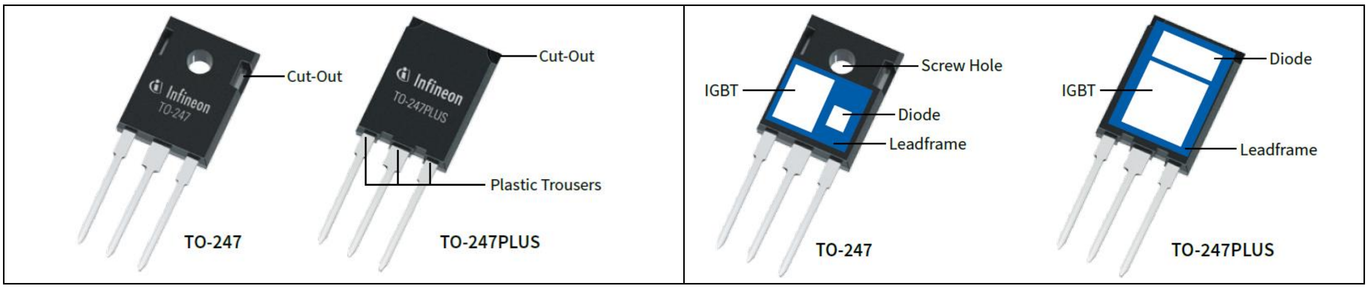


Figure 2 Overview of Infineon's TO-247PLUS and standard TO-247 package families

In addition, the total backside active thermal pad area has been increased to improve the heat dissipation capabilities of the package. The creepage distance has also been improved with so-called "plastic trousers" and special cut-outs of the mold compound at the upper corners. Figure 2 shows details of the new TO-247PLUS package; additional information about the package performance and assembly guidelines can be found in [3].

The TO-247PLUS package meets the growing demand of welding machines for higher power density and higher efficiency. Before TO-247PLUS package release, it was a big challenge for discrete devices to accommodate inverter solutions for ≥ 250A welding machines, achieving these high power levels only by paralleling devices. However, using Infineon's new TO-247PLUS IGBT devices allows designers the possibility to reduce the number of devices needed by simplifying the system's mechanical assembly.

In summary, the new TO247PLUS IGBTs improve power density (~ 50% compared to standard TO-247 package), reduces the number of parallel devices, system PCB and heatsink size, and increases system reliability and lifetime.

Infineon's comprehensive 40 A to 75 A 1200 V TO-247PLUS Co-Pack IGBT portfolio is based on the enhanced IGBT technologies shown in Figure 3. The optimized characteristics of these IGBT technologies meet perfectly the requirements of medium-power welding machines.

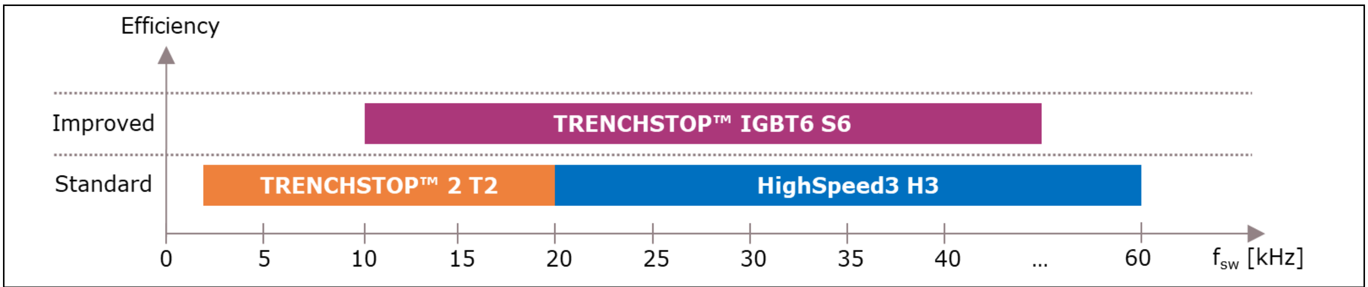


Figure 3 Infineon 1200 V IGBT technologies in TO-247PLUS package

2 400 A welding power supply using TO-247PLUS IGBT devices

This section discusses an improved 400 A welding machine power supply using TO-247PLUS IGBT discrete devices. The system solution is based on a well-known thermal design concept in which, with the purpose of increasing the heat dissipation, the discrete IGBTs without any electrical isolation are directly mounted on the heatsink. This unconventional thermal design increases power density enabling an extension of the range of applications of discrete IGBTs to power levels typically achieved by IGBT modules, reducing the cost of welding machines.

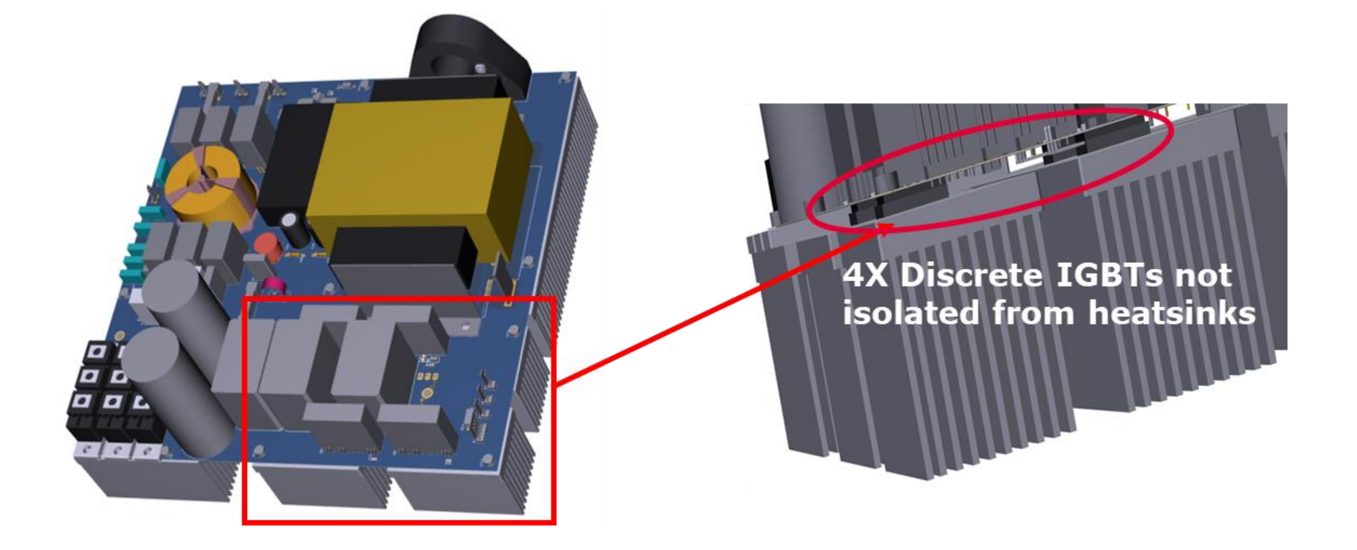


Figure 4 400 A welding machine power supply concept with discrete IGBTs not isolated from heatsink

To demonstrate the capacity and performance of the proposed IGBT discrete solution in medium-power welding machines, a 400 A welding machine power supply has been designed and assembled. It is a three-phase system with a full-bridge DC/DC converter. The topology has been selected bearing in mind that it is the most commonly used topology for this specific power level. The power converter uses four Infineon 1200 V TRENCHSTOP™ IGBT6 TO-247PLUS discrete devices, IKQ75N120CS6, mounted without additional insulation material on the heatsink, as shown in Figures 4 and 5. In addition, the diodes on the output rectification are emitter-controlled diodes TO-247 IDW100E60 from Infineon as well. In summary, the complete power inverter solution is based on discrete devices, however, the improvement analysis of the proposed discrete solution is entirely focused in the performance of the full-bridge converter IGBTs.

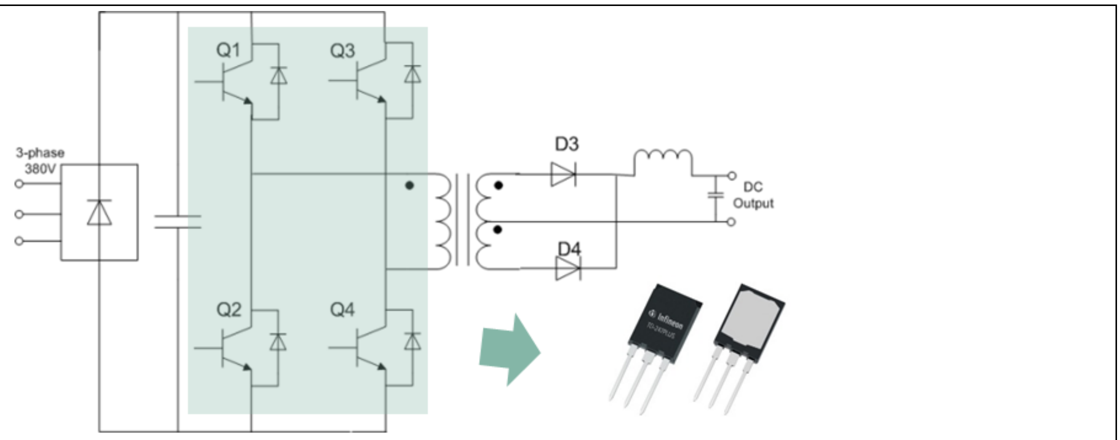


Figure 5 Simplified schematic of 400 A welding machine power supply using TO-247PLUS IGBTs

400 A welding power supply using TO-247PLUS IGBT devices

Table 3 shows the specifications of the designed 400 A welding machine power supply using IKQ75N120CS6 TO-247PLUS IGBTs without isolation from heatsink.

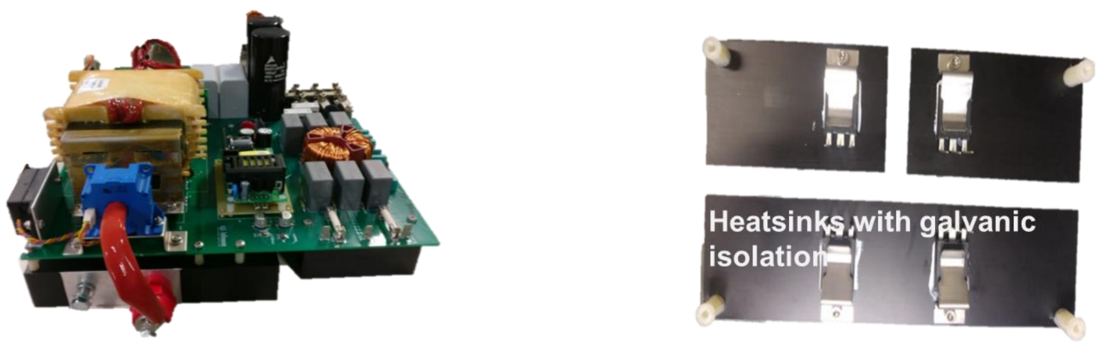
Table 3 Specification of 400 A welding machine power supply

Parameter	Value
Input supply voltage	3-phase, AC 380 V ±15%, 50/60 Hz
Input power	25.7 kVA
Output current range	40 - 400 A_{DC}
Output voltage	36 V_{DC} at 400 A_{DC}
Duty cycle (10 min, 40°C ambient)	60%, 400 A_{DC}
Open circuit voltage	80 V
Efficiency	80%
Power factor	0.7
Switching frequency	10 to 40 kHz
Operating ambient temperature range	-10 to +40°C
Dimensions (L x W x H)	323 x 322 x 170 mm^3

2.1 Welding machine power supply performance

To confirm and demonstrate the proper performance of the 400 A welding machine power supply with the proposed discrete solution, shown in Figure 6, the machine was operated under the following test conditions:

- Input voltage = 3 phase, 400 V_{RMS}
- Output power = 400 A_{DC} / 36 V_{DC}
- R_{gate} ON/OFF = 4.7 Ω
- Switching frequency = 20 kHz
- Test time = 60% duty cycle = 6 min ON / 4 min OFF
- $T_{ambient}$ = room temperature
- Forced-air cooling for heatsink = 119 CFM
- RCL load



a) 400 A welding machine power supply b) Heatsinks arrangement with galvanic isolation

Figure 6 400 A welding machine power supply using IKQ75N120CS6 IGBTs not isolated from heatsink

400 A welding power supply using TO-247PLUS IGBT devices

Figure 7 shows typical waveforms of high-side IGBT during one switching period of the welding machine power supply.

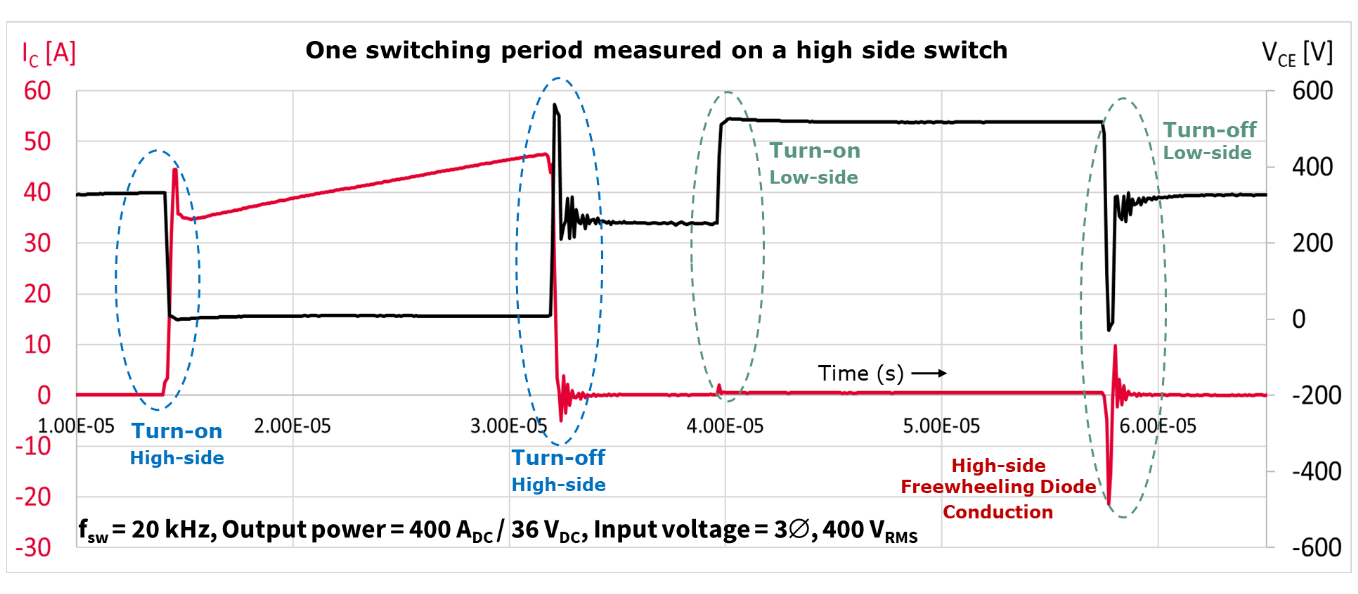


Figure 7 400 A welding machine power supply operation: one switching period example

Moreover, the temperature profiles illustrated in Figure 8 show the excellent and stable performance of the proposed solution using discrete IGBTs without isolation from the heatsink.

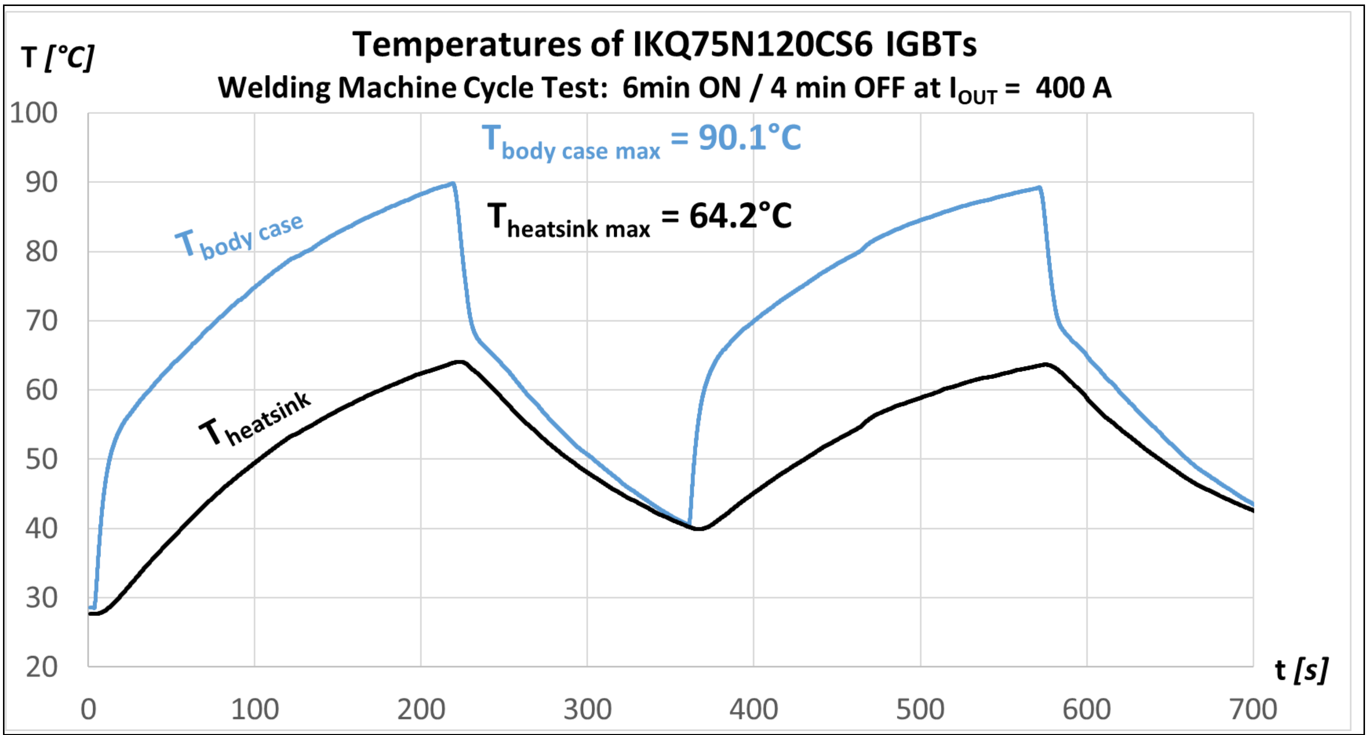


Figure 8 Thermal performance of IKQ75N120CS6 IGBTs in 400 A welding machine power supply

The thermal performance of IKQ75N120CS6 TO-247PLUS IGBT in the welding machine power supply indicates the actual benefits of the proposed solution using IGBT discrete devices directly mounted on the heatsink, without electrical isolation. The thermal results show a maximum body case temperature, $T_{body\ case}$ = 90°C at T_{amb} = 25°C. Therefore, if we consider that the typical maximum ambient temperature $T_{amb\ max}$ specification for welding machines is 40°C, we can conclude that discrete IGBTs will perform easily within the maximum junction temperature $T_{j\,max}$ specification of 175°C for this specific IGBT device.

As a reference, note that the TO-247PLUS body case $T_{body\,case}$ is very similar to the junction temperature T_j as confirmed in [3].

In summary, the test results confirm and demonstrate that the proposed solution using discrete devices without electrical isolation mounted on the heatsink in the power converter enables discrete IGBTs devices to handle power levels typically achieved by IGBT modules only in welding machine power supplies.

3 Proposed discrete solution vs. typical module solution

To validate the proposed discrete solution and the performance of TO-247PLUS discrete IGBTs in a medium-power welding machine, a popular 400 A welding machine using a typical module solution is used to compare and confirm the proposed solution of discrete IGBTs without electrical isolation mounted on the heatsink. The 400 A welding machine used for the evaluation consists of a full-bridge power converter using 2X 34 mm 75 A IGBT modules in a half-bridge configuration, and 2X 200 A diode modules in a common cathode configuration for the output rectifier. Figure 9 shows the actual manufactured 400 A welding machine used for the evaluations.

Figure 9 Inside view of popular 400 A welding machine in the market used for the evaluations

3.1 TO-247PLUS IGBTs performance in actual 400 A welding machine

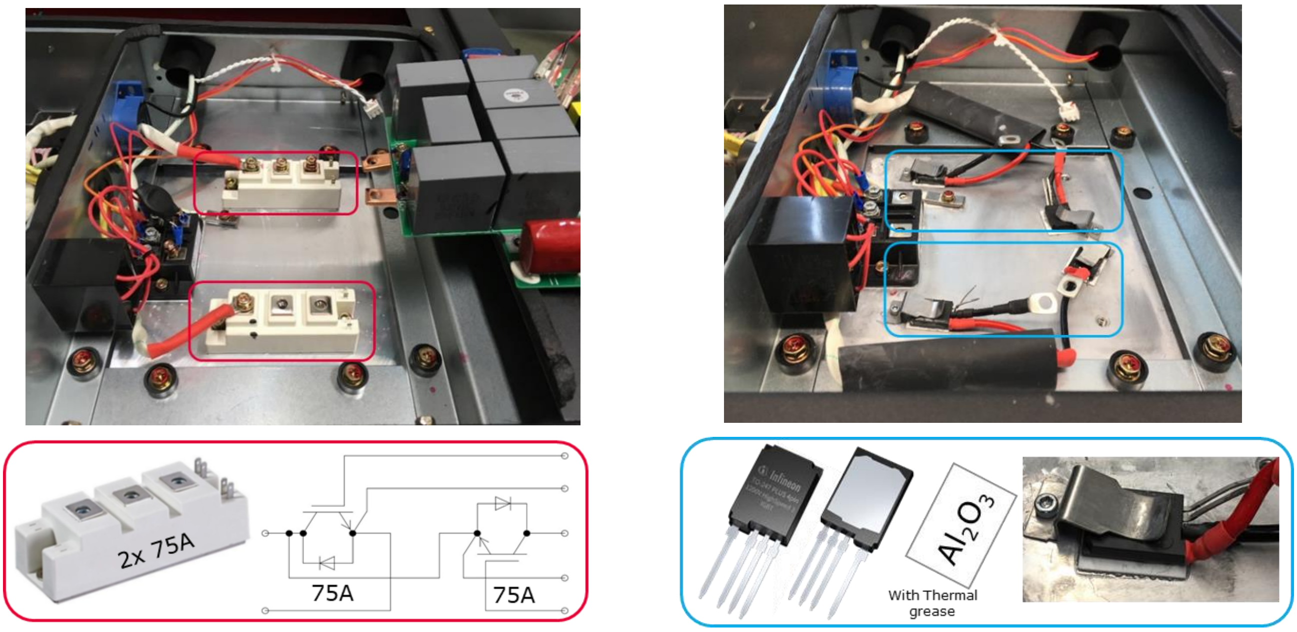
To compare both the discrete and the module solutions, the IGBT modules of the welding machine under comparison were replaced with TO-247PLUS IGBTs. However, due to the characteristics of the welding machine design, it was very challenging to achieve a full heatsink isolation for the proposed discrete solution. For this reason, and to provide the best relative comparison, the discrete devices were mounted using an aluminum oxide ceramic insulation material, AOS 247 from Fisher Elektronik, with excellent thermal resistance of 0.3 K/W [5], and additional thermal grease KP98 from Kerafol [6], with a thermal resistance of 0.01 K/W.

To achieve similar gate-driving test conditions as with the welding machine under comparison using an IGBT module with Kelvin emitter pin, the TO-247PLUS device version with Kelvin emitter pin IKY75N120CS6 was used.

In brief, only the power switches were changed for the performance test comparison. The gate-driving conditions such as V_{GE} and R_{gate} values, and the thermal system such as original heatsinks and forced-cooling conditions, were maintained as in the original welding machine design.

Figure 10 depicts details of the test setup of the welding machine using IGBT modules vs. the discrete solution using IKY75N120CS6 TO-247PLUS device with aluminum oxide ceramic insulation material.

Proposed discrete solution vs. typical module solution



a) Original module solution   b) IKY75N120CS6 TO-247PLUS discrete solution

Figure 10 Original welding-machine module solution vs. IKY75N120CS6 TO-247PLUS discrete solution

For reference, Table 4 provides the key parameters from the data sheet of the original IGBT module in welding machine vs. TO-247PLUS IGBT used for evaluation, IKY75N120CS6.

Table 4 Key parameters of original welding machine IGBT module vs. IKQ75N120CS6 TO-247PLUS

Parameter	Original welding machine IGBT module	IKY75N120CS6 TO-247PLUS
V_{CE}	1200 V	1200 V
I_c @ 25°C	150 A	150 A
I_c	75 A (@ 80°C)	75 A (@ 175°C)
$I_{c\text{-pulse}}$	150 A	300 A
$V_{CEsat\ typ}$ @ 75 A, 25°C	3.10 V	1.85 V
$V_{CEsat\ typ}$ @ 75 A, 125°C	3.45 V	2.15 V
$E_{on\ IGBT}$	4.16 mJ (@25°C), 5.82 mJ (@125°C)	2.2 mJ (@25°C), 3.3 mJ (@ 175°C)
$E_{off\ IGBT}$	2.17 mJ (@25°C), 3.44 mJ (@ 125°C)	2.95 mJ (@25°C), 5.3 mJ (@ 175°C)
$T_{j\ max}$	150°C	175°C
$R_{th(IGBT\ j\text{-}c)}$	0.19 K/W	0.17 K/W
$R_{th(Diode\ j\text{-}c)}$	0.49 K/W	0.41 K/W
Weight	150 g	6 g

Table 4 shows that the IGBT module has lower E_{off} switching loss performance, however IKQ75N120CS6 TO-247PLUS IGBTs have significantly lower V_{CEsat}. In addition they have a capacity for higher pulse current $I_{C\ pulse}$ and higher junction temperature $T_{j\ max}$ of 175°C. They are significantly lighter as well.

3.2 Test results: Discrete solution vs. module solution

The test results of the evaluation performed on the 400 A welding machine show that it is possible to design and meet the requirements of medium-power welding machines using discrete IGBTs. The discrete solution shows similar or even improved performance when compared with the IGBT module solution of the medium-power welding machine used in the test. For instance, Figure 11 shows the thermal test results of the evaluation with the IKY75N120CS6 TO-247PLUS discrete solution. The results show acceptable and stable performance at the maximum 400 A output current specification for the welding machine, i.e., $T_{body\ case}$ = 100°C at T_{amb} = 25°C. Hence, referring to [2], T_j ~ 100°C at T_{amb} = 25°C. Once again, if we consider that the typical maximum ambient temperature $T_{amb\ max}$ specification for welding machines is 40°C, we can conclude that performance will not exceed the IGBT's maximum junction temperature $T_{j\ max}$ specification of 175°C.

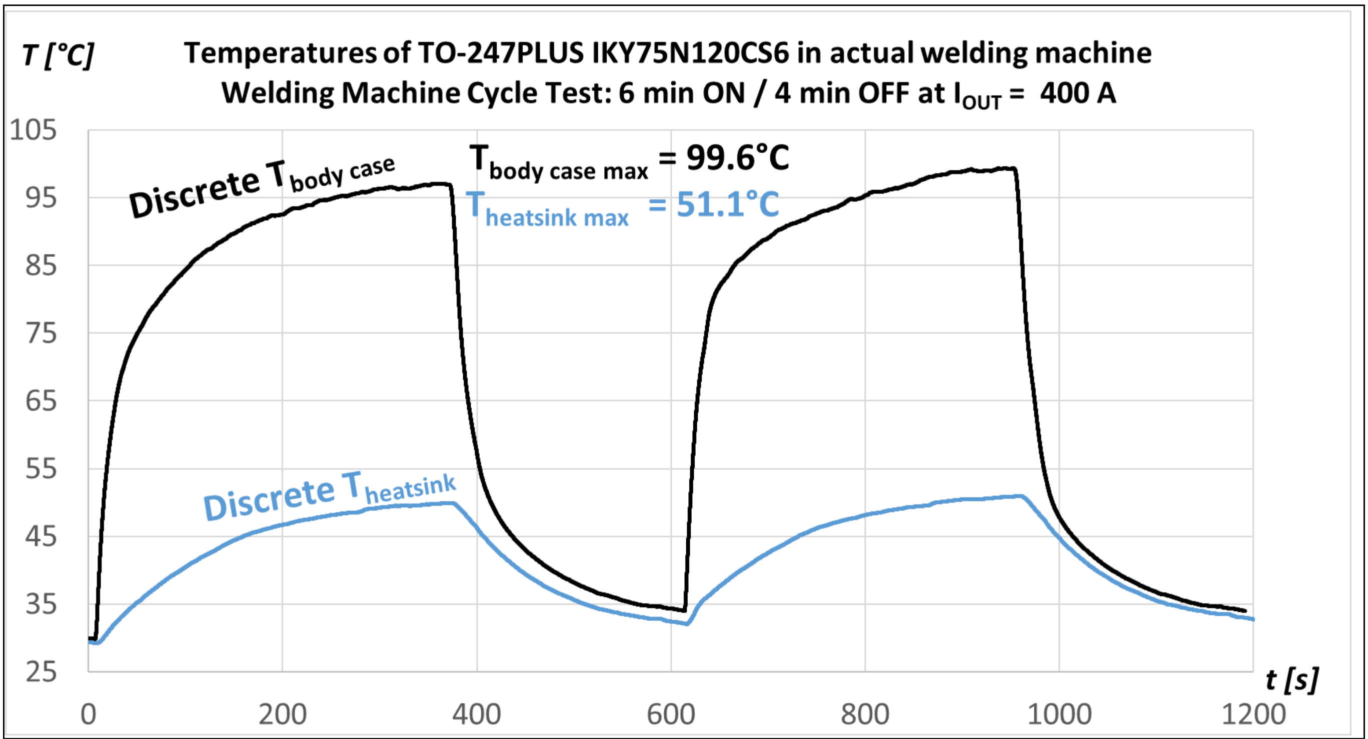


Figure 11 IKY75N120CS6 TO-247PLUS thermal performance in actual 400 A welding machine

Figure 12 illustrates the comparison of IKY75N120CS6 TO-247PLUS vs. module solution. The comparison was done using the heatsink temperature at the welding machine's maximum 400 A output current specification. The heatsink temperature comparison shows 3°C higher temperature with original module solution, i.e., the total power losses of the IKY75N120CS6 TO-247PLUS solution are lower than with the module solution.

In summary, if the discrete device solution using insulation material achieves better performance than the typical module solution, we can expect that the performance of the discrete solution without insulation material will be significantly better.

Proposed discrete solution vs. typical module solution

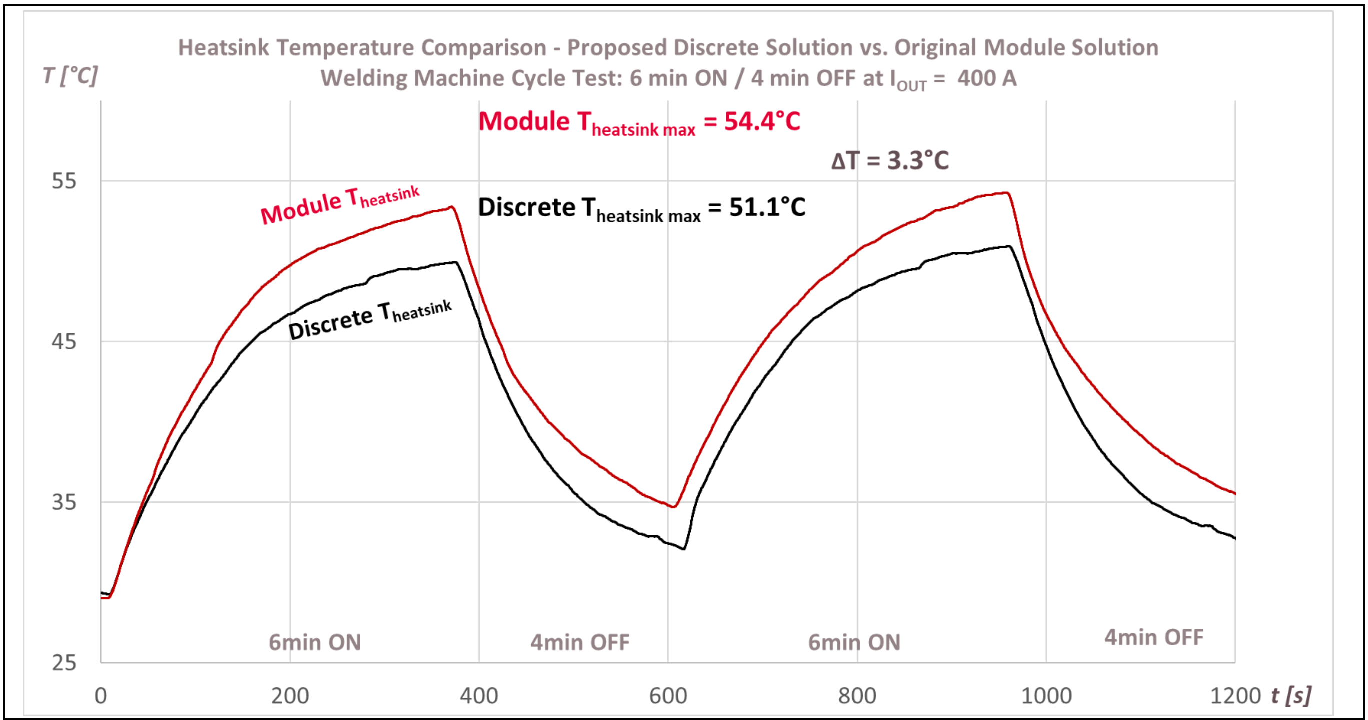


Figure 12 Heatsink temperature results, IKY75N120CS6 TO-247PLUS solution vs. original module solution

3.3 TO-247PLUS with and without insulation material - R_{th} comparison

In order to have an accurate estimation of the thermal performance of the proposed solution using discrete IGBTs without electrical isolation from the heatsink in the currently manufactured welding machine, an additional test has been performed to measure the thermal resistance of junction to heatsink, $R_{th(j\text{-}heatsink)}$ of TO-247PLUS with and without aluminum oxide ceramic insulation material. The following table shows the thermal resistance results:

Table 5 $R_{th(j\text{-}heatsink)}$ of TO-247PLUS device with and without Al_2O_3 insulation material

Parameter	**Thermal grease + AL_2O_3**			**Thermal grease only**		
- M4 screw mounted at 1 Nm torque - Mounting clip pressure = 119 N - Heatsink forced-cooling						
Applied power [W]	9.78	43.84	67.93	9.80	44.17	68.63
Junction temperature T_j [°C]	34.1	75.4	103.8	32.8	65.6	89.9
Heatsink temperature $T_{heatsink}$ [°C]	27.0	39.9	47.8	27.0	38.9	48.4
Delta temperature [°C]	7.1	35.5	56	5.8	26.7	41.5
$R_{th(j\text{-}heatsink)}$ [K/W]	**0.73**	**0.81**	**0.82**	**0.59**	**0.60**	**0.60**

Hence it is evident there is a significant improvement of the thermal resistance without any isolation material. The thermal resistance $R_{th(j\text{-}heatsink)}$ improves by 0.2 K/W, i.e., about 25%.

Therefore, we can conclude there is a significant performance improvement with IKY75N120CS6 TO-247PLUS without insulation material in the currently manufactured welding machine. This confirms even further the advantages and benefits of the discrete solution without isolation from heatsink over the typical module solution in medium-power welding machines.

3.4 Simulation results: Discrete solution vs. module solution

To finally confirm the performance of proposed discrete solution vs. original module solution in the actual manufactured welding machine, a simulation model of the DC-to-DC converter with realistic thermal and electrical parameters closest to real welding machines has been developed to estimate the junction temperature T_j performance. The simulation results shown in Figure 13 validate the simulation model performance with temperature results very similar to real measurement. In addition, the results confirm the significant difference of IKY75N120CS6 TO-247PLUS thermal performance with and without any insulation material in actual manufactured welding machine. The results show a T_j difference of ~ 32°C with and without insulation material.

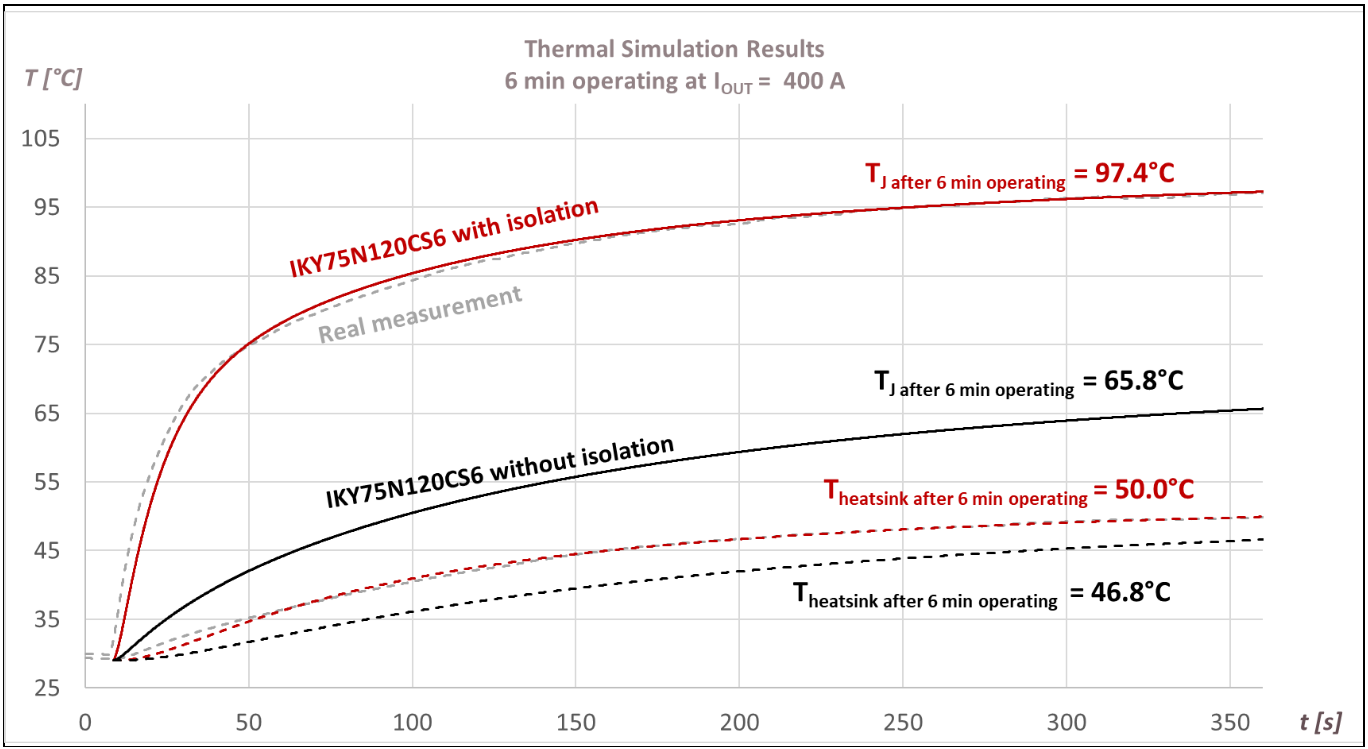


Figure 13 Simulation results of IKY75N120CS6 TO-247PLUS with and without insulation material

Figure 14 shows the simulation results of the proposed discrete solution without any electrical isolation from heatsink vs. the module solution of actual manufactured welding machine.

Proposed discrete solution vs. typical module solution

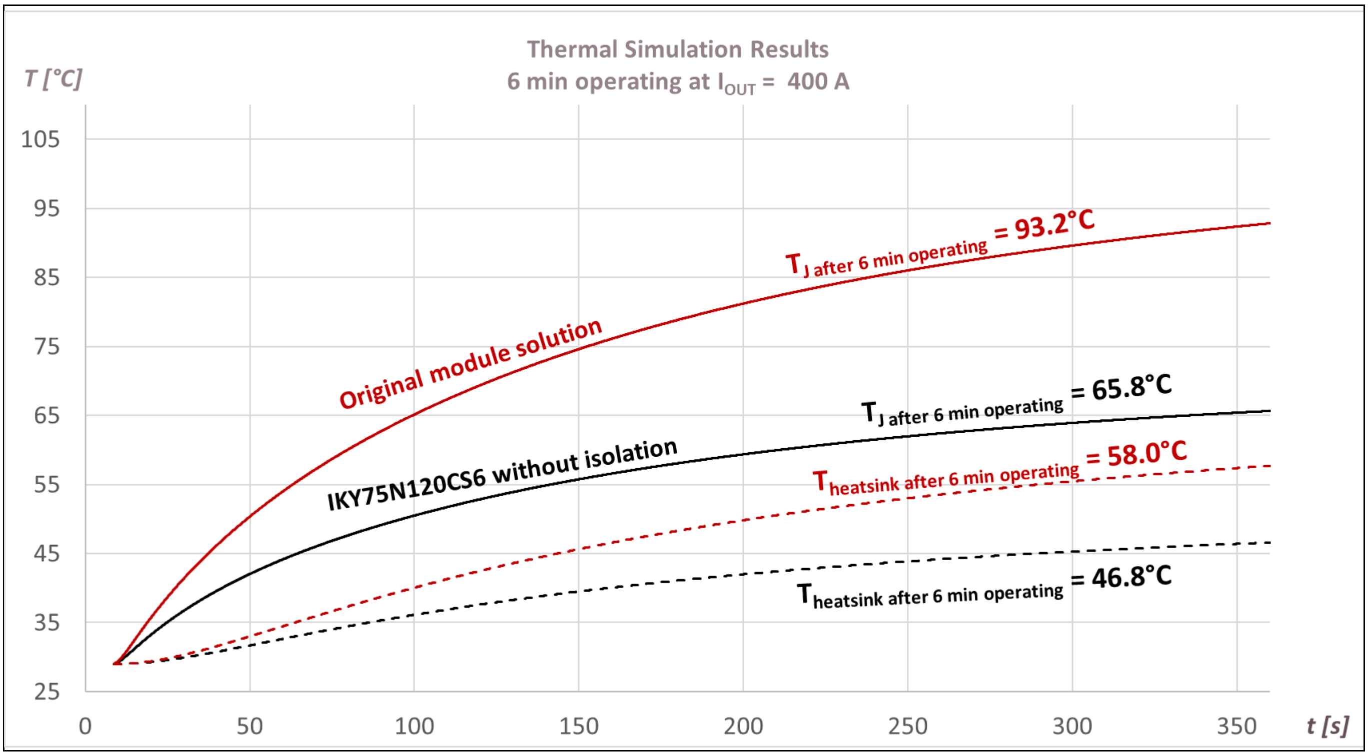


Figure 14 Proposed discrete solution vs. module solution of actual manufactured welding machine

The results show significantly better thermal performance of proposed discrete solution in comparison with the model solution. Specifically, the proposed discrete solution shows ~ 27°C lower T_j vs. the module solution of an actual manufactured welding machine.

4 Conclusion and future work

An improved solution with discrete IGBTs has been proposed and demonstrated. The solution is based on a well-known but not often used thermal design concept for increasing heat dissipation, in which the discrete IGBTs are directly mounted on the heatsink without electrical isolation. Furthermore, the proposed solution with Infineon's new TO-247PLUS discrete package has demonstrated improvements due mainly to the higher current-carrying capability of the package. The performance of the proposed solution is confirmed with a 400 A full-bridge welding power supply using Infineon's IKQ75N120CS6 1200V TO-247PLUS package devices.

The test results confirmed that the proposed discrete solution increases power density and enables higher output current with lower current-rated devices. Hence, it allows an extension of the application range of discrete IGBTs to power levels typically achieved by standard IGBT modules, reducing the cost of medium-power welding machines.

With regard to future work, Infineon is permanently researching, evaluating, and innovating to fulfill its commitment towards the efficient use of energy. This is the case for welding-machine applications, where investigations are in progress on specific subjects such as synchronous rectification for the output rectifier, PWM control schemes, and topologies design options, to name a few, in order to improve the efficiency and power density, performance, and cost of welding-machine systems. Furthermore, a very comprehensive study is in progress to validate the superior performance of discrete devices vs. modules at power-cycling test conditions, a very critical subject to improve the reliability and lifetime of welding machines.

5 Appendix: Designed 400 A welding power supply schematics

The following section shows the schematics of the designed and assembled three-phase 400 A welding machine power supply, shown in Figure 6, with a full-bridge DC/DC converter using discrete IGBTs not isolated from heatsink.

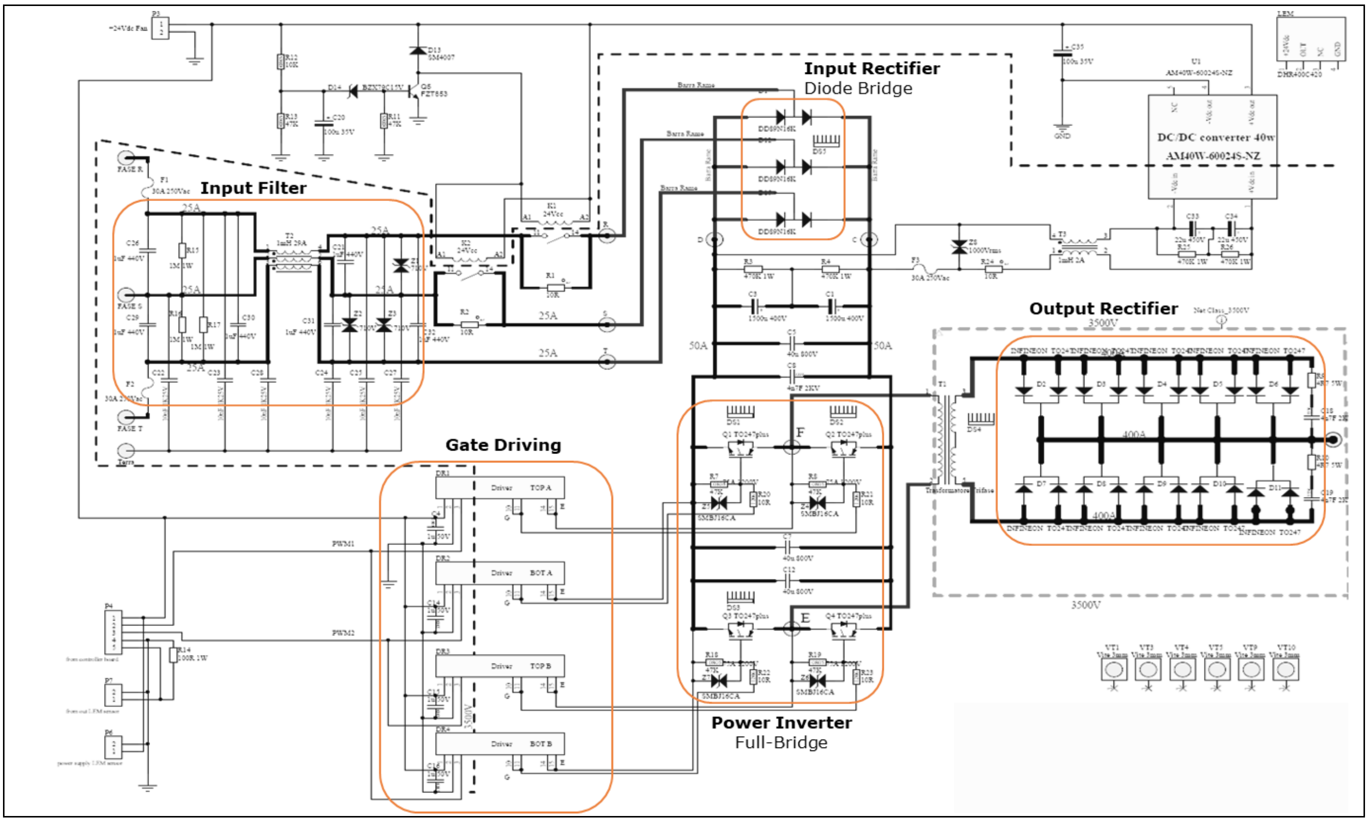


Figure 15 Power circuit schematic

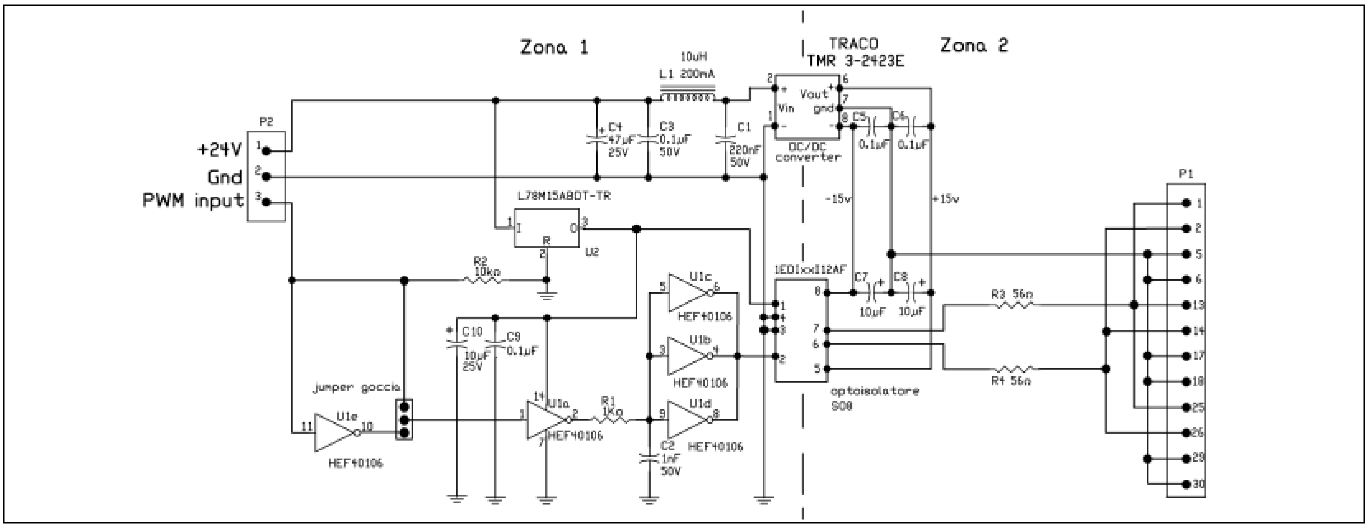


Figure 16 Gate driver circuit schematic

Appendix: Designed 400 A welding power supply schematics

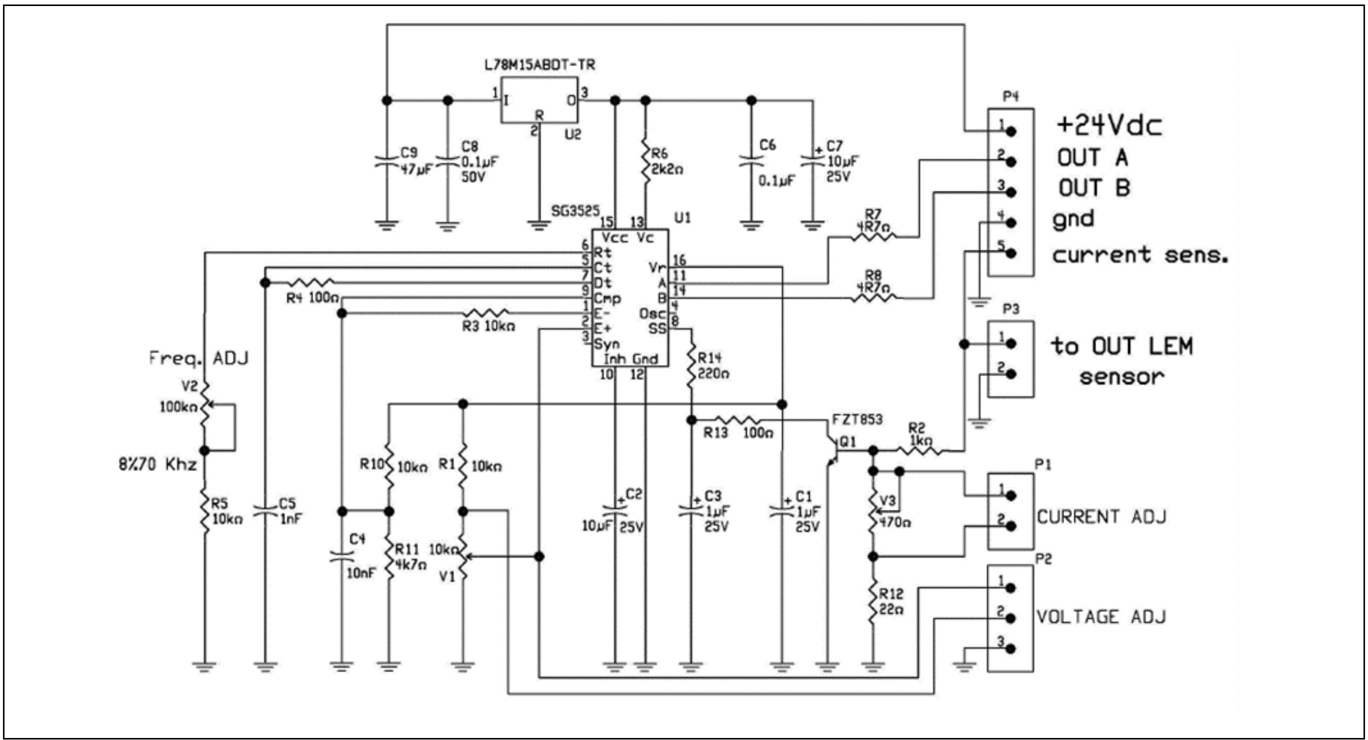


Figure 17 PWM controller circuit schematic

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