AN4638
Application note

Welding machines: V and HB series IGBTs on two-switch forward converters

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Introduction

The two-switch forward converter (also known as asymmetrical half-bridge forward converter) is a popular topology often used in industrial welding machines with low-to-medium power requirements. The inverter stage in this hard-switched forward topology includes two transistor switches and two fast recovery diodes placed at each end of the high-frequency power transformer primary winding. The output stage at the transformer secondary side includes rectifier diodes and an LC filter operating as a buck converter, hence the DC voltage output signal has a small switching ripple.
The new ST 600 V/650 V IGBT technologies with trench gate field-stop structures are specifically tailored to meet the needs of this topology in single phase main, where the working frequency is generally set to ~60kHz, exhibiting the highest performance in comparison with the principal competition thanks to the excellent trade-off between switch-off energies and the $V_{CE(sat)}$ parameter.

This paper shows the test results for the field-stop high-speed technology V and HB series IGBTs analyzed on two different 4 kW and 6 kW manual metal arc (MMA) welding platforms with a two-switch forward topology configuration implemented for the power converter sections. An evaluation of the thermal and electrical performance in terms of power dissipation and switching characteristics of these IGBTs under full-load steady state operation is provided, as well as different working conditions of the boards.

Modern DC welding machines generally use switch-mode DC/DC power supplies to output a regulated high DC current and low DC voltage, with an isolation transformer which provides galvanic isolation between the input and output sections. Thanks to the new field-stop high-speed technology IGBTs, switch mode DC/DC power supplies for welding machines can now operate at high frequencies with low losses by providing rapid rise and fall times during the turn-on and turn-off switching transients.

Due to the high switching frequencies involved, welding equipment can be rendered lighter, more portable and less expensive by mounting smaller high frequency transformers and magnetic components. IGBTs must be selected not only on the basis of the maximum current capability and blocking voltage rating, but also the low values for the on-state saturation voltages in order to minimize the conduction power losses, particularly during maximum working power conditions. Finally, the effective reduction of conduction and switching losses for the power switches in the converter section leads to higher overall welding machine system efficiency and improved performance [*1*, *2*].

The high-power capacity and function mode of the transformer and switches render the two-switch forward converter among the most suitable configurations for DC/DC converters meeting the requirements of arc welding machines and suitable for use in the current supply for MMA welding processes, as described further on.

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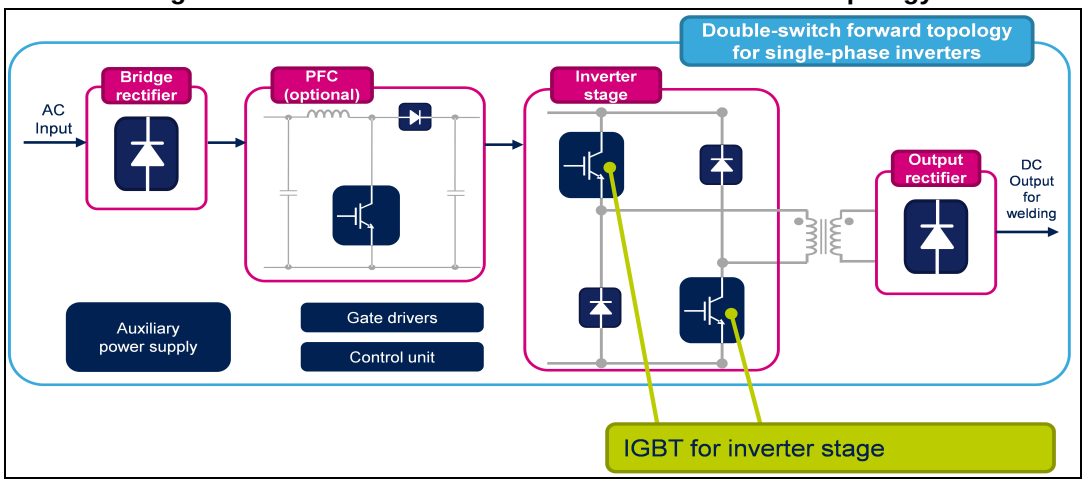
1 Two-switch forward converter general concepts

The two-switch forward converter circuit employs two power switches to energize the primary side of a ferrite high frequency transformer and two freewheeling diodes to discharge the magnetization inductance of the primary side winding of the transformer. At the secondary side, transformer output voltage is initially scaled, then rectified by the diode bridge rectifier (half-bridge or full-bridge, depending on the application requirements) and finally filtered to provide smooth DC voltage or current. The two power switches are simultaneously switched on and the gates are driven by square waves with variable duty cycle based on the pulse width modulation technique. The duty cycle variation therefore allows voltage modulation on the output of the power supply and, consequently, the welding current modulation[3].

In welding applications, the forward converter is normally designed to operate in continuous-conduction mode (CCM) for the output inductor current at a fixed switching frequency (the output inductor lends continuous-mode operation to the current as the main IGBT switches turn on before this output current ceases). In particular, a single-ended converter requires a larger transformer and output inductor for welding machines above the 4 kW output level.

Figure 1 illustrates the two-switch forward converter configuration.

Figure 1. IGBTs mounted on a double switch forward topology.



The input voltage seen by the inverter stage used in this power range is the output voltage of a power factor correction (PFC) converter, typically in the 380 V – 400 V range for single phase welding machine inverters.

The double switch forward configuration is preferable to alternative configurations because power switches in the off state are subject to a voltage stress equal to the DC input voltage V_{DC} (or V_{bulk}) and the transformer design is more straightforward than other isolated topologies because no additional winding to reset the magnetic flux in the core is required. Moreover, since the two recirculating diodes clamp the input voltage, no snubber circuit is required and any overshoot beyond the input voltage can be managed with a proper circuit layout to minimize stray inductances.

Other distinctive features include:

- The clamp diodes recover the magnetizing energy stored in the core during on-time, which is fed back to the supply; therefore, any voltage spikes generated by leakage inductance are clamped to the DC input bulk voltage level.
- No IGBT antiparallel co-packaged diode conduction is required under any operating condition.
- The maximum duty cycle is limited to 50% to guarantee full demagnetization of the ferrite transformer during t_{off} (transformer reset) to prevent magnetic flux saturation.
- The core flux only operates in one quadrant of the BH loop.
- The configuration is unable to operate in zero-voltage switching (ZVS) mode because this limits its operation frequency.

Even if the IGBT voltage stress should, in theory, be clamped to the maximum DC input bulk voltage level and recycled back to the input capacitor via the activation of the fast recovery diodes, the IGBTs may actually see an additional spike during turn-off switching which is affected by the leakage inductance energy, the switching speed, and the circuit layout. Leakage inductance is difficult to control and often varies in production[*4*].

Refer to “Topology equations and device selection” in the Appendix, which details some useful equations for the selection of the IGBTs used in testing.

2 STMicroelectronics V and HB series IGBTs

The 600 V/650 V trench gate field-stop technology IGBTs (V and HB series respectively) were tested in two different single phase main welding machine platforms implementing the two-switch forward converter configuration, as detailed below:

- IGBTs STGW40V60DF and STGW60V60DF (TO-247 package) were two-by-two parallel tested on a 4 kW application board, switching at ~63 kHz.
- IGBTs STGW40H65DFB and STGW60H65DFB (TO-247 package) were two-by-two parallel tested on a 6 kW application board, switching at ~58 kHz.

The following table shows the voltage and current ratings found in the electrical characteristics section of the respective component datasheets.

Table 1. Voltage and current rating of IGBTs

Device selection	Techno/ series	Blocking voltage rating (V_{CES} max)	Current rating (I_C@100°C)	Main benefits	Key products
Primary switches Q1 and Q2	Trench gate field stop “V” series	600 V	40 A – 60 A	– very high switching speed – low thermal resistance – safe paralleling operation – very fast soft recovery antiparallel diode – low saturation voltage – tail-less switching off – positive $V_{CE(sat)}$ temperature coefficient	STGxnnV60DF
	Trench gate field stop “HB” series	650 V	40 A – 60 A	– high switching speed – low thermal resistance – safe paralleling operation – very fast soft recovery antiparallel diode – very low saturation voltage – minimized tail current – slightly positive $V_{CE(sat)}$ temperature coefficient	STGxnnH65DFB

3 Electrical specifications of welding machines

Manual metal arc (MMA) welding involves striking an arc between a covered metal electrode and a workpiece, and is a highly popular arc welding process for small domestic projects or light professional use.

The primary function of a welder power source is to provide sufficient output power or current to melt the joint at the end of the electrode so as to weld the metal. To achieve this, an arc welding machine power supply is required to control the load current/voltage over a wide range, with a sufficiently high current (50 A – 500 A) but a relatively low voltage (10 V – 50 V and 80 V for ignition). The load range of the arc welding process is such that the power supply is expected to operate from open-circuit (no-load condition) to short-circuit (when the electrode is in contact with the workpiece for a short span of time). Also, transitions occur during the striking of the arc, rapid arc length changes and metal transfer across the arc, and the power supply must respond to these changes rapidly.

The following technical data relates to the two single-phase manual metal arc welding machine platforms, 4 kW (MMA160) and 6 kW (MMA200), tested during the analysis performed with the 600 V/650 V trench gate field-stop technology IGBTs, V series and HB series respectively.

Table 2. Technical data for welding machines

MMA160		MMA200	
Parameter	**Value**	**Parameter**	**Value**
Mains voltage	1 phase 230 V ± 10%	Mains voltage	1 phase 230 V ± 15%
Frequency	50/60 Hz	Frequency	50/60 Hz
Open circuit voltage	95 V	Rated input current	38.2 A
Electrode nominal power at 100%	3.5 kW	Output current adjustment	15 A – 190 A
TIG DC nominal power at 100%	2.3 kW	Output voltage	20.6 V – 27.6 V
Electrode arc voltage	20.2 V – 26.4 V	No-load voltage	94 V
TIG arc voltage	10.2 V – 16.4 V	Duty cycle at 40 °c	20%
Max current	27 A	Efficiency	85%
Power factor	0.85	Power factor	0.73

Details regarding welding processes and arc control on the welding machines are extensively explained in [5,6].

4 Description of test conditions and analyses

The switching performance and temperature characteristics of the IGBT devices were evaluated at full load steady state operation in “open board” conditions at room temperature (25 ºC), as well as various operating conditions for the board by stepping the input/output power level up to the maximum value, with a 220 V_{AC} input main voltage and 50 Hz frequency.

In both the analyses, the full load condition was reproduced by connecting the output of the board with a resistive load composed of a series of power resistances arranged in parallel and with a ceramic base in order to reach the total value of about 145 mΩ. During the tests, a fan was used to maintain a constant temperature and therefore help keep total resistance value constant. This external fan was mounted away from the welding machine to avoid any influence on the thermal performance of the devices. Moreover, in all the tests performed, the IGBTs were screwed to the same heatsink as per the original mounting arrangement.

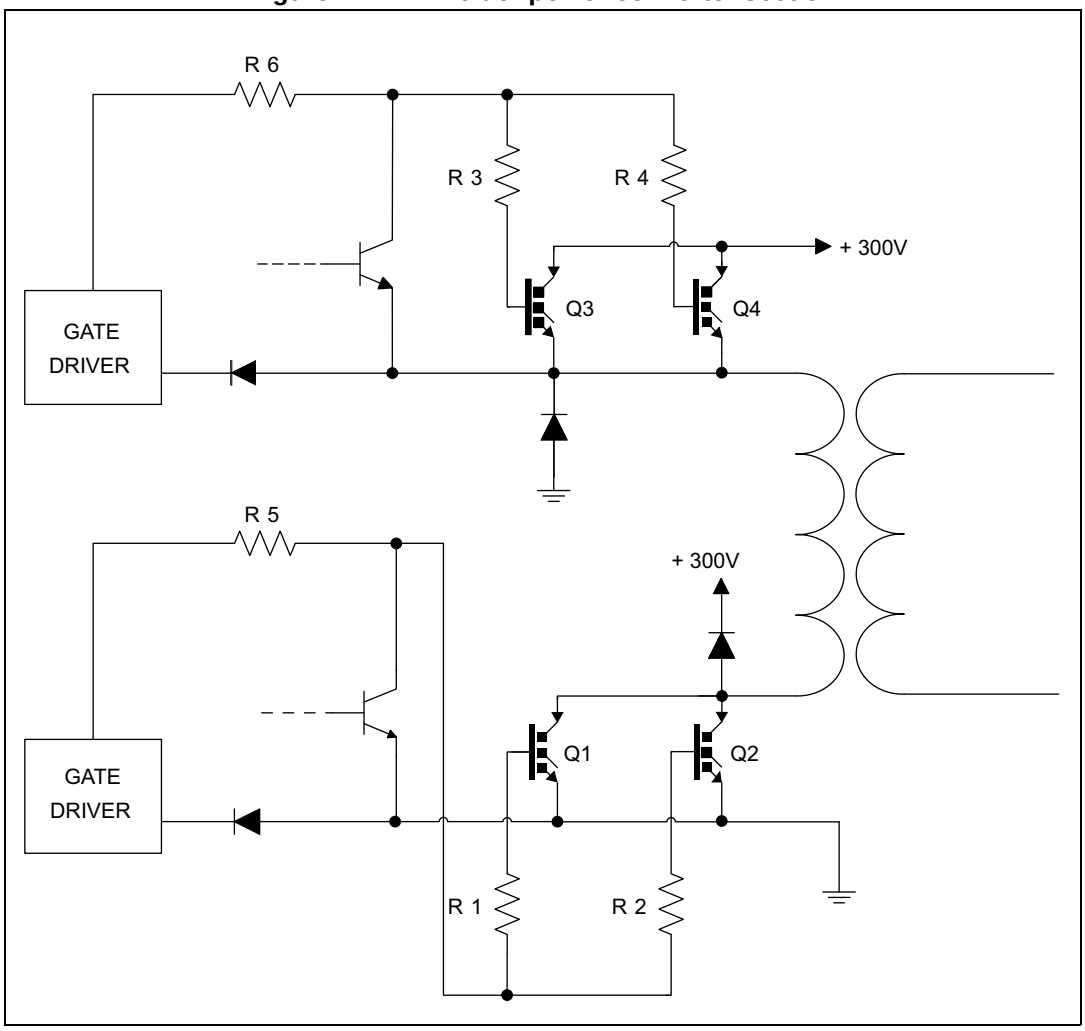
In open board conditions (removing the external metal cover of the welding machine) at ambient temperature (~25 °C), the measurements were performed with the IGBTs connected with wires in order to allow the insertion of the probes for the scope to record the signals. Under these conditions, particular attention was focused on the electrical behavior of parameters like the V_{CE} voltage across collector and emitter pins, the collector (or emitter) current I_C and the V_{GE} voltage across gate and emitter pins during normal operation.

5 V series IGBTs on a 4 kW welder

Analysis of the V Series IGBTs was developed under the following test conditions:

- switching frequency fixed to ~63 kHz
- gate driving resistances R1, R2, R3, R4 = 4.7 Ω and R5, R6 = 2.2 Ω
- power ranging from 2 kW up to maximum input power
- output load resistance ~145 mΩ

Figure 2. 4 kW welder power converter section



Four IGBTs were connected two by two paralleled in a “double switch forward DC-DC converter” configuration of the 4 kW single phase welding machine board tested in “free air” (open board without housing) conditions with ambient temperature T_{AMB} = 25 °C (+/- 2 °C). The signal waveforms and temperatures were acquired and measured for the two paralleled low-side devices, Q1 and Q2.

Below are the results achieved from the analysis performed with the STGW40V60DF IGBTs tested on a 4 kW welder. The table below lists the main parameters for these components;

for more details regarding these IGBTs, please refer to the relevant datasheet available at www.st.com.

Table 3. STGW40V60DF main parameters

Device	Package	BV_{CES}	I_C@100 °C	$T_{j\text{-}max}$	V_{CESAT}(typ) @25 °C
STGW40V60DF	TO-247	600 V	40 A	175 °C	1.8 V

5.1 Overview of thermal and electrical measurements

The electrical measurements for the input power, input current and power factor (PF) taken by the power meter at the input of the welder as well as the temperature and time values achieved by the STGW40V60DF IGBTs during the electro-thermal analysis carried out on the board are detailed in the following table and graph; the operating conditions for the application (220 V_{AC}, 50 Hz input) are:

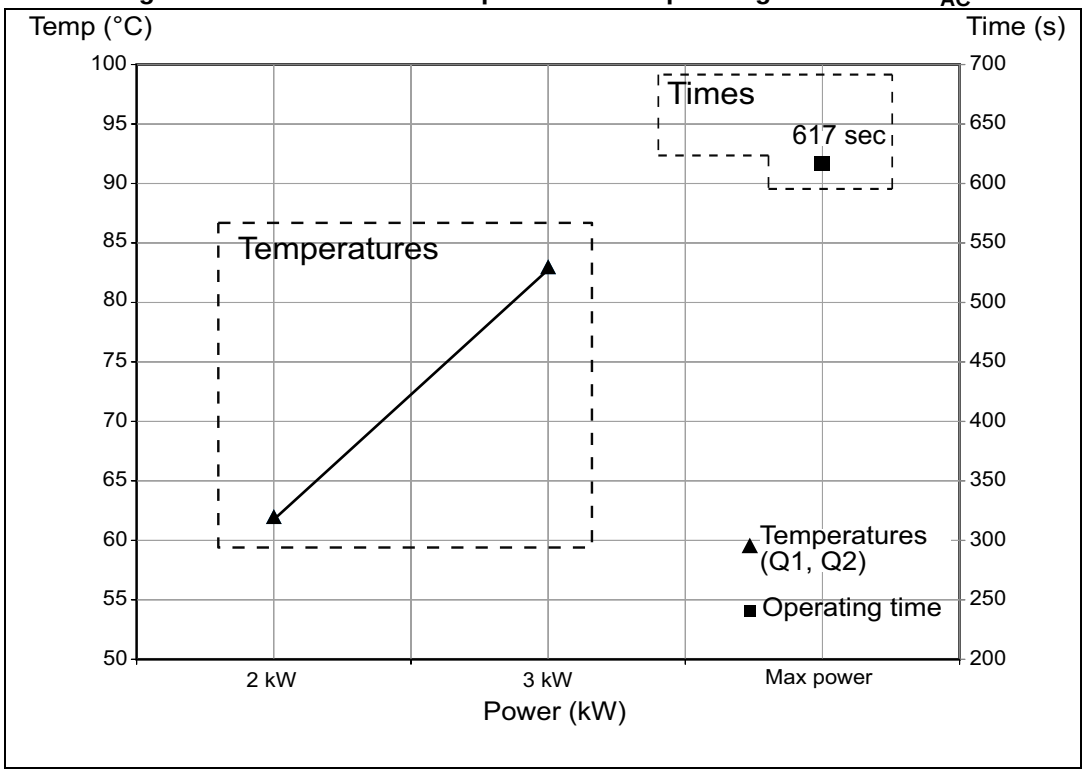
- full load steady state operation under 2 kW input power conditions;
- full load steady state operation under 3 kW input power conditions;
- full load steady state operation under maximum power absorbed in input conditions.

The case temperatures measurements were taken by a thermo camera once thermal stability had been achieved by the devices running on the board. Operating times were measured for maintained maximum input power (~4 kW), starting from a cold state condition, until the thermal protection interrupted operation.

Table 4. Thermal and electrical measurements

Device	Input power (kW)	Input current (A)	PF	Temp (°C)	Time (min: s)
STGW40V60DF	2	15.4	0.58	62°	
	3	22.2	0.61	83°	
	~3.8(max)	26.3	0.66		10 min17 s

Figure 3. STGW40V60DF temperature and operating time at 220 V_{AC}

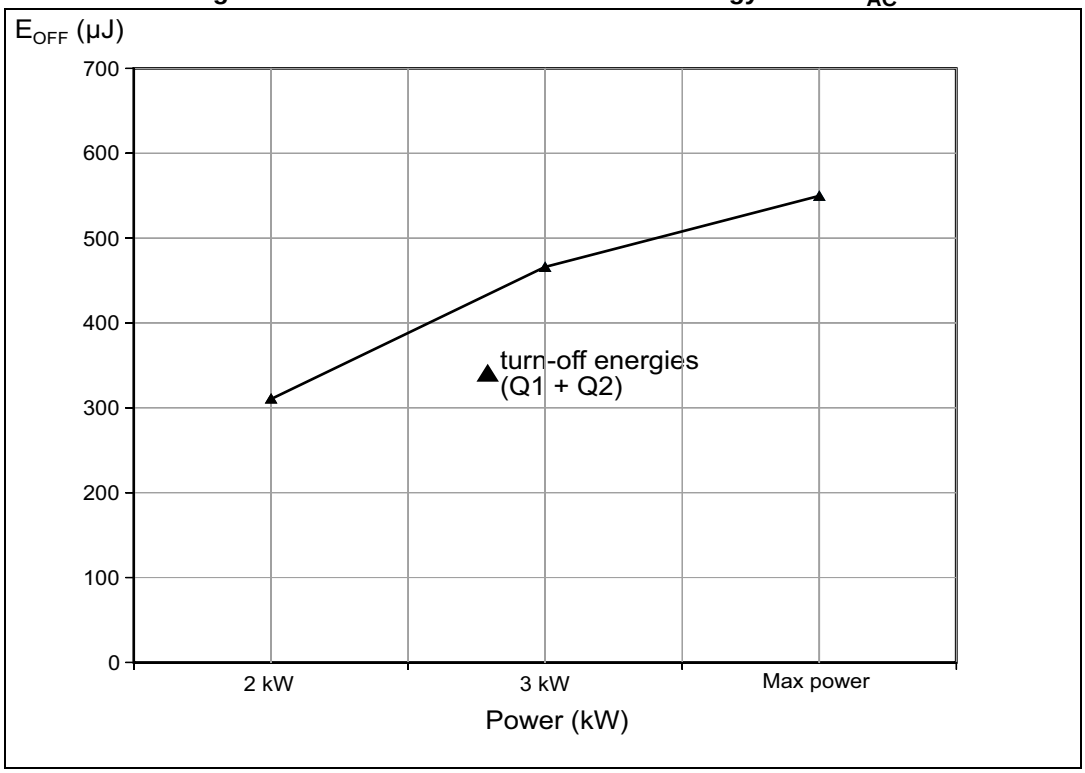


The measurement of the total turn-off energies (taken as the mathematical sum of the energies related to each device of the low-side pair of tested IGBTs) are detailed in the table and graph below, starting from 2 kW up to the maximum power level of 220 V_{AC} input main voltage at 50 Hz.

Table 5. STGW40V60DF total turn-off energy measurements

Device (Q1 + Q2)	E_{OFF} @ 2 kW (µJ)	E_{OFF} @ 3 kW (µJ)	E_{OFF} @ max power (µJ)
STGW40V60DF	311	466	550

Figure 4. STGW40V60DF total turn-off energy at 220 V_{AC}



The STGW40V60DF IGBTs demonstrate highly satisfactory thermal behavior, achieving 83 °C approx. for 3 kW input power, while operation at maximum input power lasted 10 minutes and 17 seconds from a cold initial state, before the thermal sensor triggered shut-down due to a breach of the maximum threshold setting (approx. 105 °C).

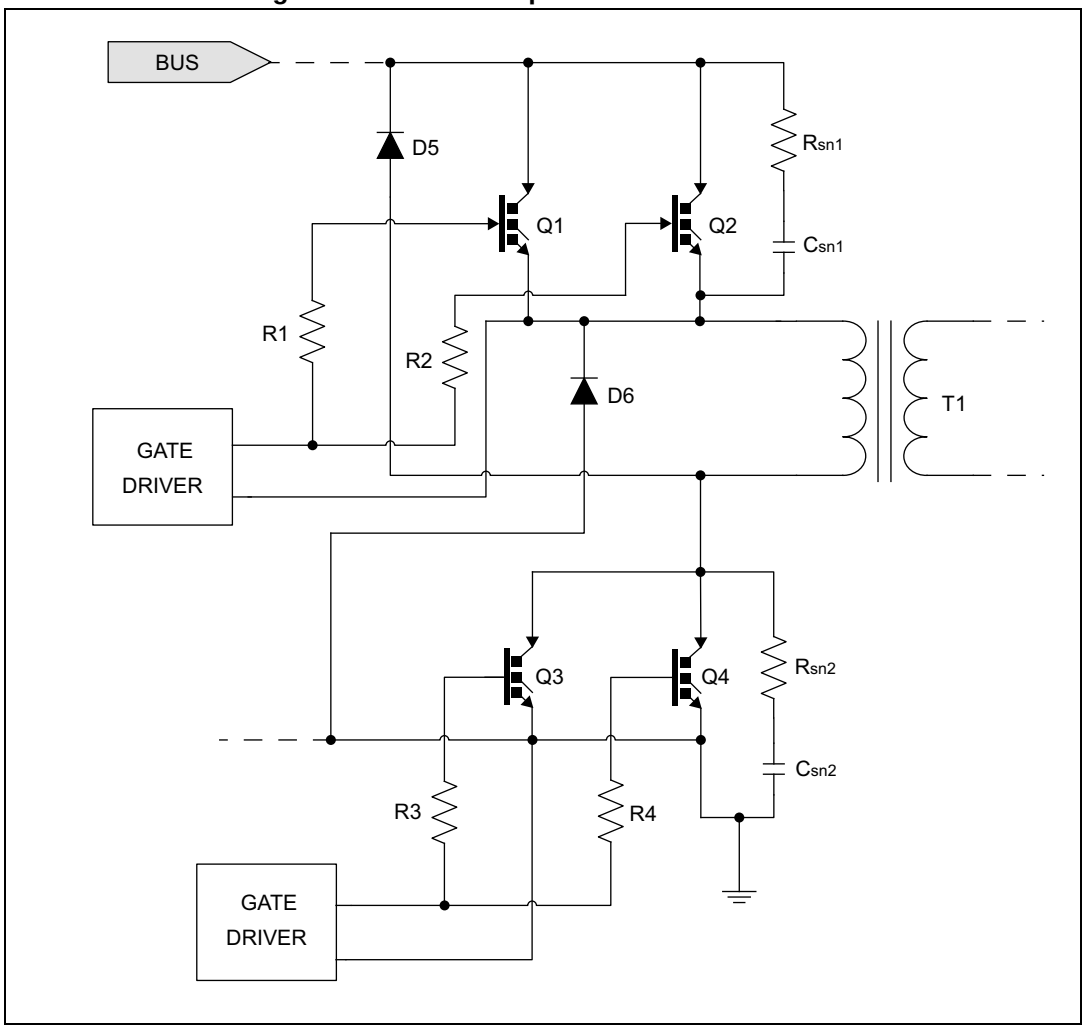
The overall electrical and power dissipation performance was very good for the two IGBTs tested: capable of switching with low amounts of turn-off energies in all the different working conditions for the application, including the worst case maximum value of ~550 µJ for turn-off switching during maximum input power operation.

6 HB series IGBTs on a 6 kW welder

Analysis of the HB Series IGBTs was developed under the following test conditions:

- switching frequency fixed to ~58 kHz
- gate driving resistances R1, R2, R3, R4 = 4.7 Ω
- RC Snubber network with R_{sn} = 22 Ω and C_{sn} = 1 nF
- power ranging from 2 kW up to maximum input power
- output load resistance ~145 mΩ

Figure 5. 6 kW welder power converter section



Four IGBTs were connected two by two paralleled in a “double switch forward DC-DC converter” configuration of the 6 kW single phase welder board tested without the external metal shroud but with the internal plastic cover, at ambient temperature T_{AMB} = 25 °C (+/- 2 °C). The signal waveforms and temperatures were acquired and measured for the two paralleled high-side devices, Q1 and Q2.

Below are the results achieved from the analysis performed with the STGW60H65DFB IGBTs tested on a 6 kW welder. The table below lists the main parameters for these

components; for more details regarding these IGBTs, please refer to the relevant datasheet available at www.st.com.

Table 6. STGW60H65DFB main parameters

Device	Package	BV_{CES}	I_C@100 °C	$T_{j\text{-}max}$	V_{CESAT}(typ) @25 °C
STGW60H65DFB	TO-247	650 V	60 A	175 °C	1.6 V

6.1 Overview of thermal and electrical measurements

The electrical measurements for the input power, output current and output power as well as the temperature and time values achieved by the STGW60H65DFB IGBTs during the electro-thermal analysis carried out on the board are detailed in the following table and graph; the operating conditions for the application (220 V_{AC}, 50 Hz input) are:

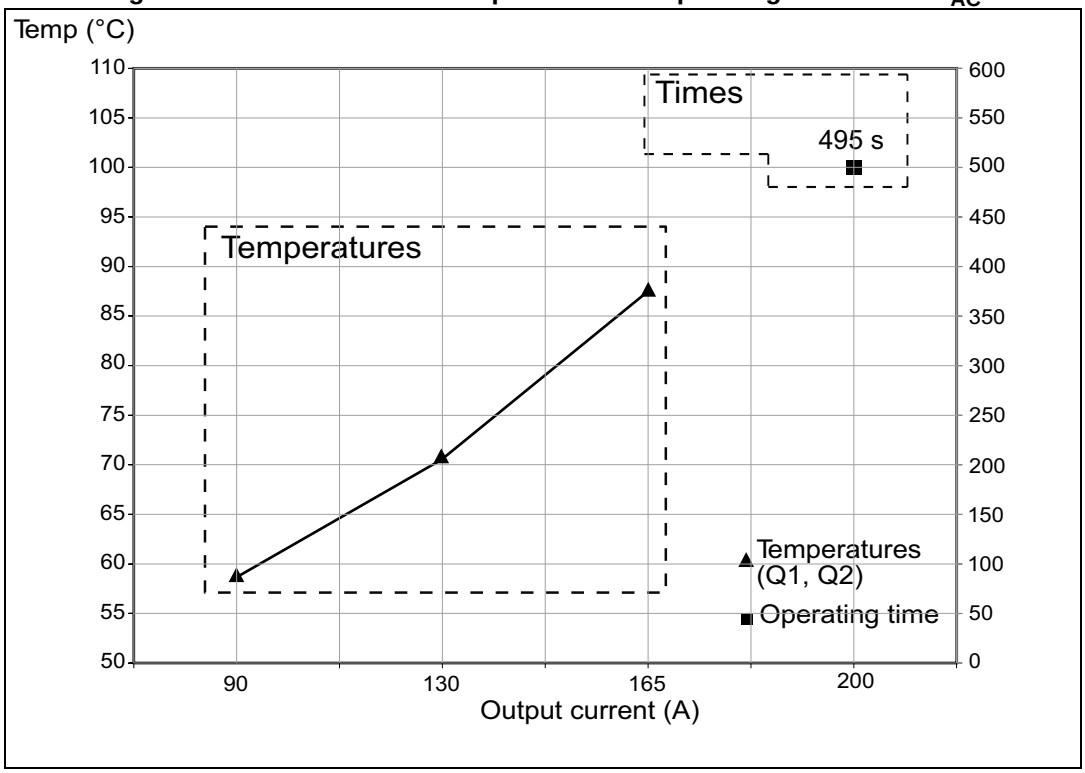
- full load steady state operation at 90 A output current;
- full load steady state operation at 130 A output current;
- full load steady state operation at 165 A output current;
- full load steady state operation at 200 A output current;

The case temperatures measurements were taken with thermocouples on the cases once thermal stability was achieved by the devices running on the board. Operating times were measured for maintained maximum output current (~200 A) until the thermal protection interrupted operation.

Table 7. Thermal and electrical measurements

Device	Output current (A)	Input power (W)	Output power (W)	Temp (°C)	Time (min:s)
STGW60H65DFB	90	~2683	~2233	59	
	130	~3864	~3172	71	
	165	~4949	~3997	87	
	200	~5883	~4624		8 min: 15 s

Figure 6. STGW60H65DFB temperature and operating time at 220 V_{AC}

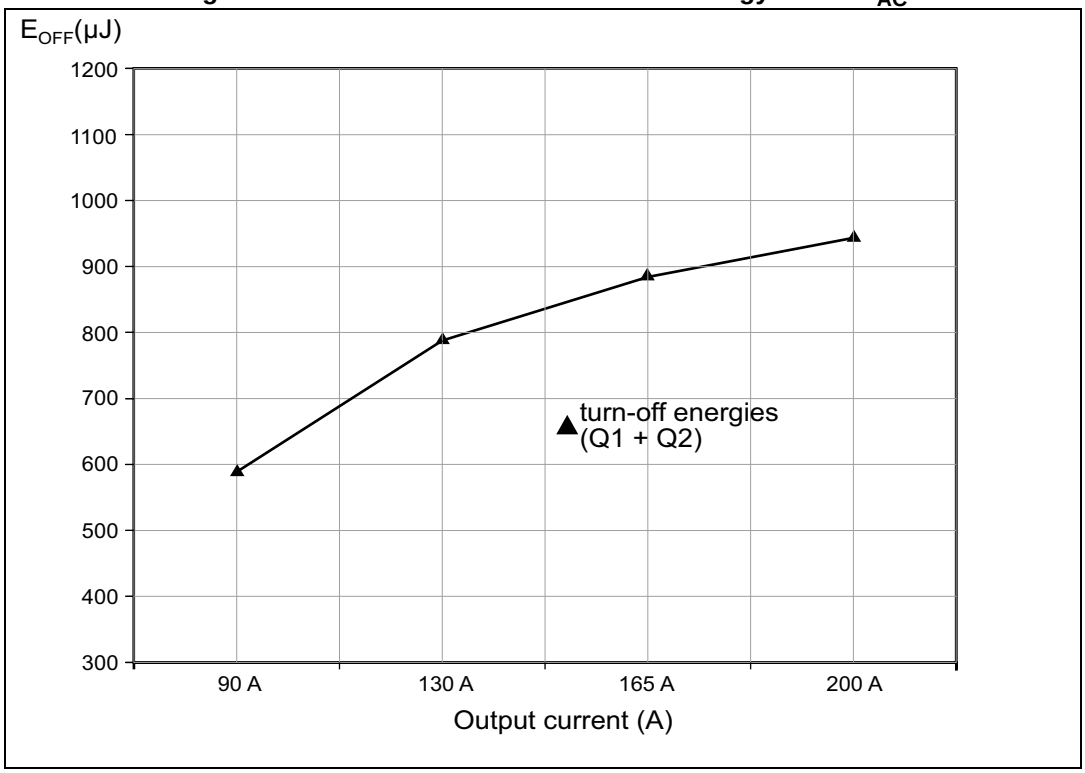


The measurement of the total turn-off energies (taken as the mathematical sum of the energies related to each device of the high-side pair of tested IGBTs) are detailed in the table and graph below, starting from 90 A up to the maximum output current of 200 A for a 220 V_{AC} input main voltage at 50 Hz.

Table 8. STGW60H65DFB total turn-off energy measurements

Device (Q1 + Q2)	E_{OFF} @ 90 A (µJ)	E_{OFF} @ 130 A (µJ)	E_{OFF} @ 165 A (µJ)	E_{OFF} @ 200 A (µJ)
STGW60H65DFB	~586	~787	~887	~947

Figure 7. STGW60H65DFB total turn-off energy at 220 V_{AC}



The STGW60H65DFB IGBTs demonstrate highly satisfactory thermal behavior, achieving 87 °C approx. for 165 A output current, while operation at maximum output current lasted 8 minutes and 15 seconds from a cold initial state, before the thermal sensor triggered shut-down due to a breach of the maximum threshold setting (approx. 105 °C).

The overall electrical and power dissipation performance is very good for the two IGBTs tested: capable of switching with low amounts of turn-off energies in all the different working conditions for the application, including the worst case maximum value of ~947 µJ for turn-off switching during maximum output current.

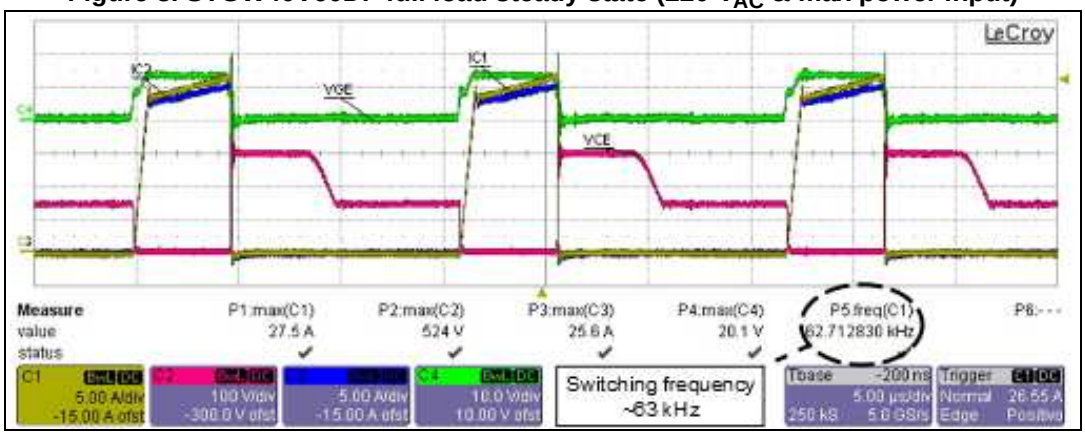
7 Electrical analysis and waveforms

The acquired waveforms below illustrate the switching performance of the tested IGBTs. Use the following color codes to interpret the information:

- Q1 collector (or emitter) current: I_{C1} signal in yellow
- Q2 collector (or emitter) current: I_{C2} signal in dark blue
- Q1 and Q2 collector-emitter voltage: V_{CE} signal in red
- Q1 and Q2 gate-emitter voltage: V_{GE} signal in green;
- Q1 instantaneous power (V_{CE} x I_{C1}): power signal in orange
- Q2 instantaneous power (V_{CE} x I_{C2}): power signal in pink
- total collector current (I_{C1} + I_{C2}): I_{C1} + I_{C2} signal in orange
- total instantaneous power (V_{CE} x (I_{C1}+I_{C2})): power signal in light blue.

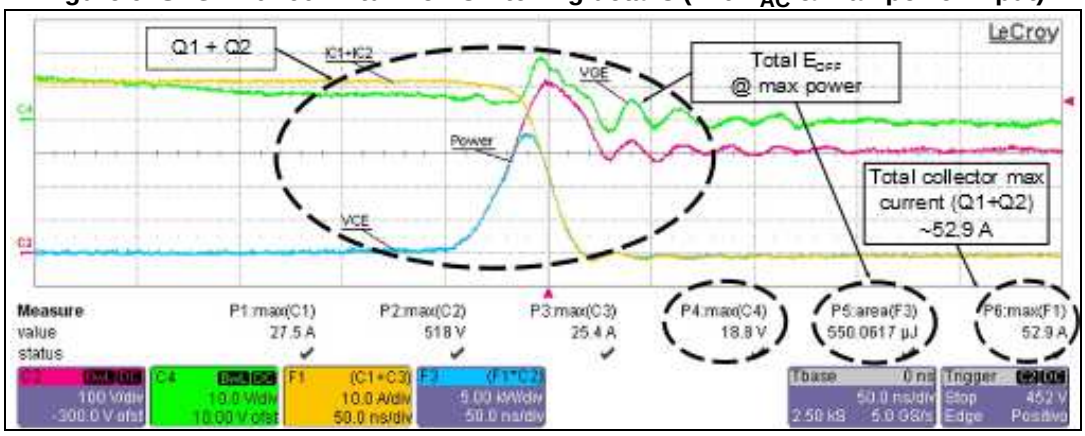
The figures below depict the signals for the 4 kW welder for both paralleled low-side devices Q1 and Q2 of the STGW40V60DF IGBTs during the steady state operation under maximum power input absorption conditions.

Figure 8. STGW40V60DF full load steady state (220 V_{AC} & max power input)



The following figure depicts the sum total current signal for the Q1 and Q2 collector currents during turn-off switching transients under maximum input power absorption conditions.

Figure 9. STGW40V60DF turn-off switching details (220 V_{AC} & max power input)



The figures below depict the signals for the 6 kW welder for both paralleled high-side devices Q1 and Q2 of the STGW60H65DFB IGBTs, during the steady state operation and switch-off phases under maximum power input absorption conditions (200 A output current).

Figure 10. STGW60H65DFB full load steady state (220 V_{AC} & max power input)

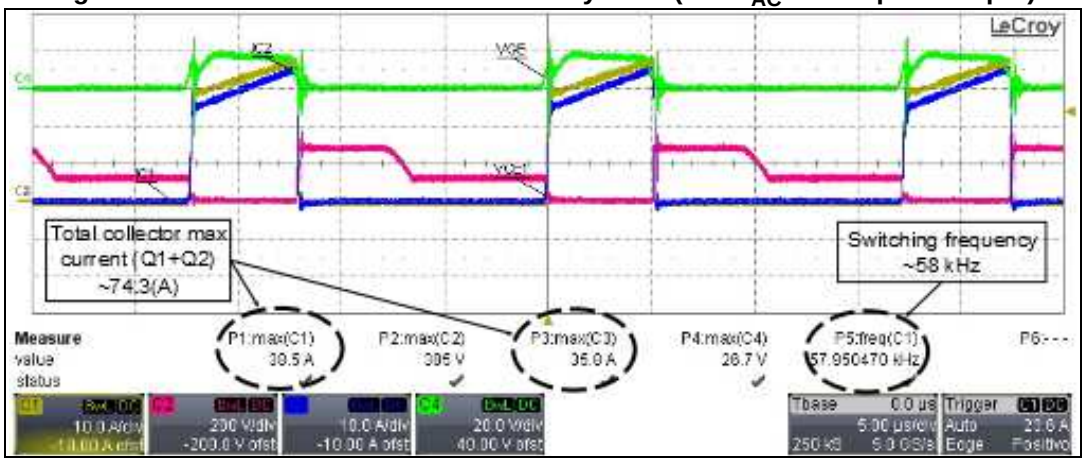


Figure 11. STGW60H65DFB Q1 turn-off switching details (220 V_{AC} & max input power)

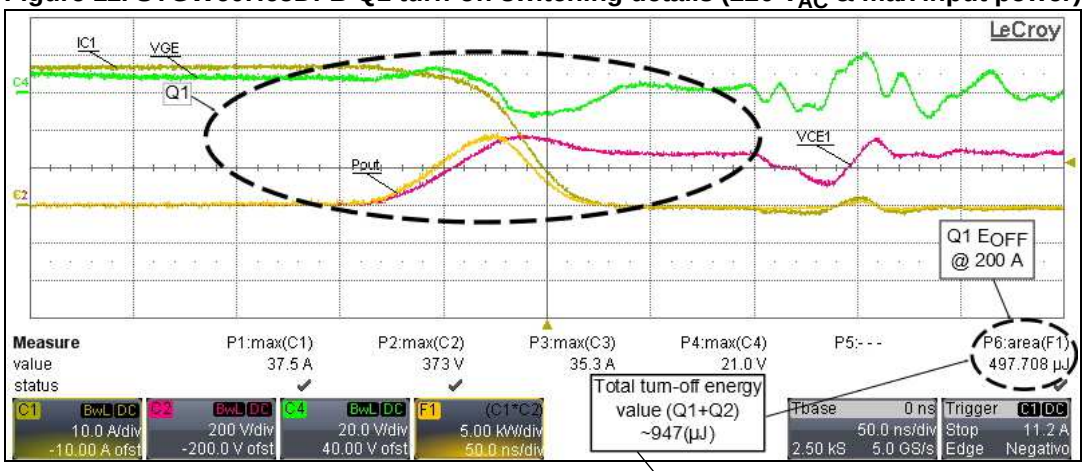
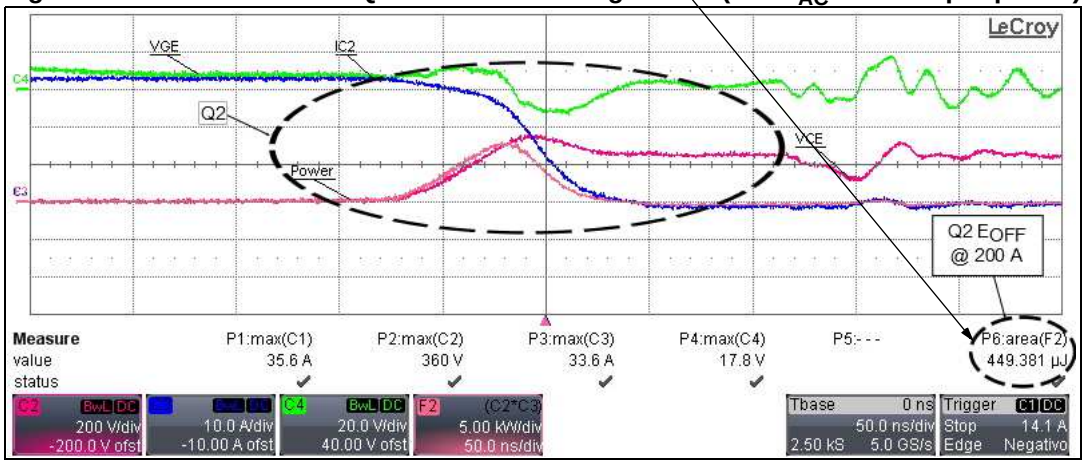


Figure 12. STGW60H65DFB Q2 turn-off switching details (220 V_{AC} & max input power)



8 Conclusion

Test results for the field-stop high-speed technology V and HB series IGBTs, analyzed on two-switch forward topology converters for welders were presented. Very good performance in terms of power dissipation and switching characteristics were achieved in normal steady-state working conditions on 4 kW and 6 kW evaluation welding platforms, thanks to the ideal trade-off between V_{CESAT} and E_{OFF} for these IGBTs.

The STGW40V60DF IGBTs showed particularly high thermal performance with around 83 °C measured under a 3 kW input power condition, while operation time was 10 min:17 s at maximum operating power (from an initial cold state of the welder) prior to thermal sensor triggering shut-down due to a breach of the temperature threshold limit. The STGW60H65DFB IGBTs also achieved acceptable temperatures of around 87 °C at 165 A output current, while the continuous operation time was 8 min:15 s at maximum output current.

The acquired waveforms clearly demonstrate considerable overall electrical performance for the V and HB series IGBTs, with low turn-off energies across the different working conditions for the welding machines, not exceeding ~550 µJ and ~947 µJ respectively during maximum operating input power and output current.

9 Bibliography

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Appendix A Topology equations and device selection

During the IGBT switch-off transients, an overvoltage appears across switches Q1 and Q2 due to transformer leakage inductance, which requires a blocking voltage capacity of more than $V_{IN,max}$ as shown below:

Equation 1

$$V_{CES} > V_{IN,max}$$

where

$V_{IN,max}$= maximum DC bus voltage

The current ratings of the primary switches are given by the following expressions in terms of $I_{C,max}$ and $I_{C,ave,on}$, where the collector current assumes a trapezoidal shape typical of the CCM working operation mode:

Equation 2

$$I_{C,max} \geq I_{C,ave,on} + \frac{\Delta I_C}{2}$$

where

$I_{C,ave,on} = \frac{I_{C,max} + I_{C,min}}{2}$ = average current during transistor on time

$\Delta I_C = I_{C,max} - I_{C,min}$ = maximum peak to peak ripple on the IGBT collector current

Equation 3

$$I_{C,ave,on} \geq \frac{P_{OUT}}{\eta \cdot V_{IN,min} \cdot D_{MAX}}$$

where

$I_{C,ave,on}$= average current during transistor on time

$P_{OUT} = \eta \cdot P_{IN}$= output power; η= efficiency; P_{IN}= input power

$D = \frac{T_{ON}}{T}$= duty cycle; D_{MAX}= maximum duty cycle

Figure 13. Two switch forward topology

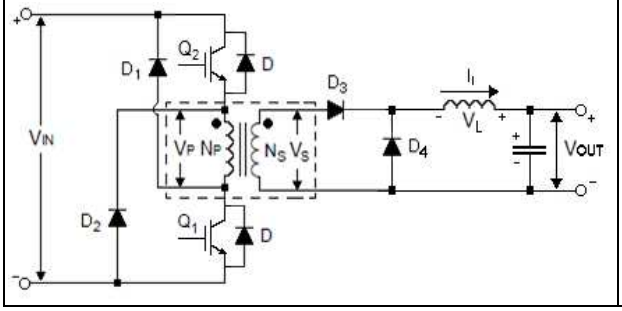
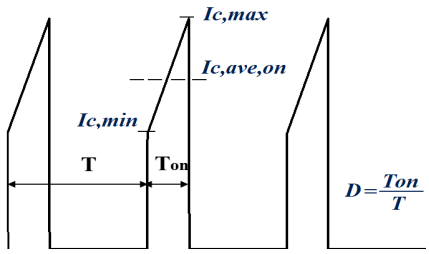


Figure 14. IGBT Collector current in CCM



Setting the following electrical conditions at maximum input power operation for the 6 kW welder:

$$P_{IN} = \frac{P_{OUT}}{\eta} = 6000\ W; \quad V_{IN,max} = 220 \cdot \sqrt{2}; \quad D_{MAX} = \frac{T_{ONmax}}{T} = 31\%; \quad \Delta I_{C,max} = 25\% \cdot I_{C,max}$$

Therefore, from the previous formulas, the maximum collector current is:

$$I_{C,ave,on} = \frac{P_{OUT}}{\eta \cdot V_{IN,min} \cdot D_{MAX}} = \frac{6000}{220 \cdot \sqrt{2} \cdot 0.31} = 62.2\ A$$

$$I_{C,max} \geq I_{C,ave,on} + \frac{\Delta I_C}{2} = I_{C,ave,on} + \frac{0.25 \cdot I_{C,max}}{2} \Rightarrow I_{C,max} \geq \frac{2 \cdot I_{C,ave,on}}{1.75} \sim 72\ A$$

The last result is valid for a single IGBT device mounted in a two-switch forward configuration, while for two devices connected in parallel, the value for each IGBT is:

$$I_{C,max} \geq \frac{72}{2} = 36\ A$$

which is the maximum operating collector current for a single IGBT device connected in a paralleled configuration for a 6 kW welder.

Revision history

Table 9. Document revision history

Date	Revision	Changes
17-Feb-2015	1	Initial release.

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