H series 1200 V IGBTs on 3-phase full-bridge DC-DC power converter welding machine

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Introduction

Nowadays from the industrial retail market a growing request arrives, the need to develop high power welding machines with advanced proprieties for the control of the output parameters and improved dynamic response capability in a wide range. These industrial power systems have to meet higher and higher performance standards concerning energy efficiency requirements and reliability.

In high voltage and high power industrial applications, usually the IGBT is preferable to the MOSFET, because the latter has high resistance at high voltage levels that increases the conduction losses and decreases the converter efficiency. However, due to the fact that the IGBT is not as fast as the MOSFET, the tail current problem could limit the use of the IGBT in high frequency applications. Power control solutions, based on the IGBT inverter technology, applied to welding machines, develop compact and reliable power sources to output a wide regulated high DC current at low DC voltage with high performance controls and low energy requirements providing a better arc stability and weld quality.

Inverter welding machines are also designed to provide multi-process capability in a single unit allowing the output parameters to be changed according to the desired characteristics and settings required for the specific welding process (i.e. MMA, TIG and MIG/MAG) with the implementation of an effective control of the power or frequency on the transformer primary side [1]. Moreover, performing an advanced output control, the inverter output power can be electronically regulated in order to allow a wide power adjustment up to around 100%, enabling a fine tuning on the basis of the specific needs and including both CC and CV characteristics in a single power supply.

The full-bridge DC-DC converter topology fully responds to the requirements of the modern arc welding machines due to high power handling capability and a better use of the transformer magnetic core and power switches.

In particular, the IGBT based full-bridge power supply solution is widely used in the arc welding retail market for the 3-phase 380 VAC medium-to-high power industrial welding machines operated in continuous current mode with simple transformer design and output power up to 10 kW to best fit a very precise control and fast dynamic response to load variations.

The new 1200 V H series of IGBTs, developed by ST with trench gate field-stop structure, is optimized for high speed and hard-switching topologies as well as it is an ideal choice to meet the requirements of 3-phase arc welding machines where the working frequency is generally higher than 10 kHz. Due to the benefits offered by this technology, the 3-phase high power supplies for welding machines can be operated at high switching frequencies providing small rise and fall times and meeting an optimum balance between conduction and switching losses to maximize the efficiency of the converters thanks to a slightly positive $V_{CE\,(sat)}$ temperature coefficient and a very tight parameter distribution.

In this paper, a verification of the thermal evaluation, power dissipation and switching characteristics of the IGBT STGWA40H120DF2 in TO-247 package long leads is presented. Experimental measurements have been carried out on a 3-phase/7.5 kW welder with a full-bridge topology configuration implemented for the power converter section.

Contents

1 Generalities on the full-bridge DC-DC converter topology for welders

Regarding to those applications with higher power ratings and rectified input voltage levels, the full-bridge DC-DC converter is usually employed in the welding machines thanks to its superior energy efficiency and magnetic circuit utilization properties *[2]*. In the full-bridge topology, the inverter stage includes four power transistor switches and four fast recovery diodes anti-parallel and co-packaged to each switch placed at the end of high frequency ferrite transformer primary winding. Energy is transferred across the transformer in balanced push-pull and when a diagonal of switches is active, the voltage on the transformer secondary winding is rectified and charges the output inductor. During the turn-off phase, the demagnetization current and the leakage energy circulate through freewheeling diode back to input *[3]*.

The control system determines the duration of the turn-on phases of transistors placed in the two full-bridge diagonals, alternatively activated by square wave gate signals with variable duty cycle based on the PWM technique to let a regulation of the voltage/current characteristics on the welding output load. In a main full-bridge inverter-based topology welding operation, the incoming AC 50/60 Hz main power (single or three-phase) is first rectified to DC and then is fed into the inverter section of the power supply where it is alternatively switched on and off by the transistor switches at high frequencies. This pulsed, high voltage, high frequency AC then is fed to the main power transformer, where it is transformed into the low voltage DC suitable for the welding process.

The *Figure 1: "IGBTs mounted on a full-bridge forward topology"* illustrates the general scheme of a full-bridge converter topology for welding machines.

Figure 1: IGBTs mounted on a full-bridge forward topology
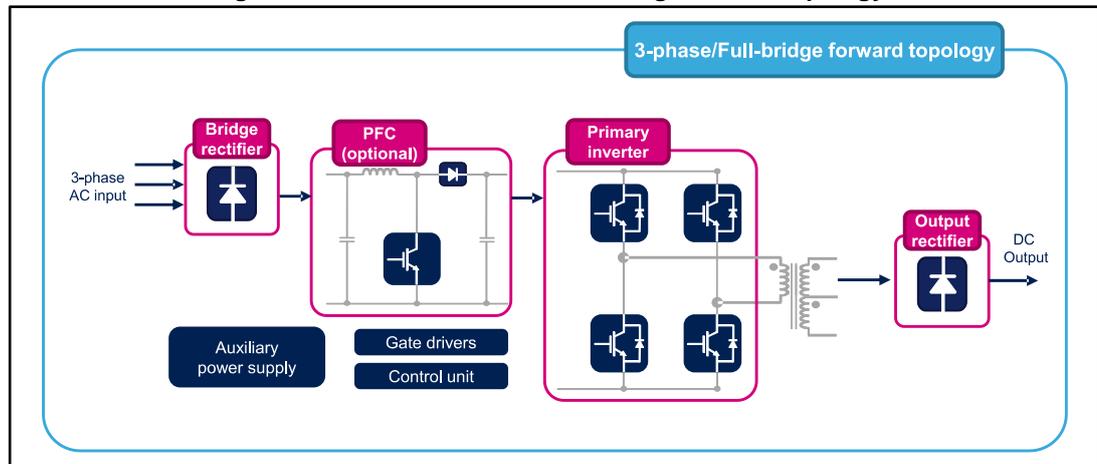
On the output of the rectifier, the maximum average of the filtered DC voltage (typically in the range from 510 V to 570 V for 3-phase applications) can be the input of a pre-regulator PFC stage in order to produce a regulated output avoiding that the voltage drops and ensuring that every available absorption of primary power is converted into usable cutting power.

In the inverter stage, diagonally opposite transistors are turned on simultaneously during alternate half cycles in order to convert the filtered DC back to an alternating voltage driving the transformer to frequencies generally higher than 10 kHz.

The iron core transformer is used to step down the pulsating primary voltage to typical arc welding voltages (<70 V_{dc}) via the transformer turn ratio as well as to perform a voltage-to-current transformation by turning the high voltage and low current AC primary power into an AC power source with high current and low voltage required to supply the secondary side [4]. This conversion allows the current amplitude to be reduced through the inverter switches and the devices operating within their maximum ratings to be kept. Transformer cross-sectional area is chosen to prevent saturation under the worst-case power transfer conditions. The switching frequency rise helps to reduce the transformer size and material cost by enabling the use of smaller ferrite cross-sectional area but it has the general limitation to increase the IGBT switching losses.

At the transformer secondary side, frequency doubling is achieved by the center-tapped winding configuration and this doubles the ripple frequency of the DC welding current, which reduces the required size of the output inductor. The output stage is connected to a high frequency rectifier stage, providing pulses having the same polarity, and followed by an LC filter generating the required setting for the welding output DC voltage signal. The output inductor helps to smooth the ripple at the lowest end of current range since the welding arc is more stable with less ripple in the current.

The full-bridge converter topology for welding applications is normally designed to operate in continuous conduction mode (CCM) for the output inductor current at a fixed switching. Additional features of the full-bridge configuration are the following:

- Power switch voltage stress in the off-state is clamped to the maximum DC input bulk voltage level (without considering any possible voltage overshoot transient during turn-off switching due to transformer leakage inductance energy, the switching speed, and the circuit layout stray inductances)
- Power switches carry the reflected load current plus the transformer primary magnetizing current during the conduction phase when the DC bulk input voltage is applied to the transformer primary
- Theoretical maximum duty cycle is limited to 50% but the 80% of a half period is chosen as design rule to prevent magnetic flux saturation and guarantee full demagnetization of the ferrite transformer during the off-time (transformer reset)
- Use of snubber circuits is required in hard-switched converters to damp the switching noise and to provide the current with an alternative path during the switch turn-off transient
- Core flux operates in two quadrants of the BH loop
- No additional winding to reset the magnetic flux in the core is required for the transformer because the magnetizing energy stored in the core during on-time and any energy stored in the leakage inductance are returned to the DC input capacitor via the activation of the fast recovery diodes
- In a pulse-width-controlled system there is a period when all the four devices are in off-state resulting in a zero-voltage across the transformer primary windings
- Configuration is able to operate in soft-switching zero-voltage transition operation mode by implementing the phase-shifted technique for the gate driving

In the isolated pulse-width modulation (PWM) DC-DC converters, transformer leakage inductance leads to switching losses when the converter operates with hard switching and decreases efficiency of the circuit due to the requirement of passive snubber elements. In the phase-shift PWM the leakages are used beneficially because the parasitic output capacitor of the power switches and the leakage inductance of the switching transformer are used as a resonant tank circuit to achieve zero-voltage across the MOSFET at the turn-on transition [5].

Refer to "Topology equations and device selection" in the Appendix, which lists some useful equations relative to the selection of the IGBTs used in testing.

2   H series 1200 V IGBTs

This new H series 1200 V IGBT leverage second-generation trench gate field-stop high-speed technology has been developed by ST to boost energy efficiency and ruggedness in the 3-phase welding applications other than various applications such as solar inverters, uninterruptible power supplies and power-factor correction (PFC) converters.

In this series the IGBTs are available in 15 A, 25 A, and 40 A versions. They also offer the option of an integrated very fast-recovery anti-parallel diode for an optimal performance in hard-switching circuits in addition to minimizing energy losses in circuits with a freewheel diode.

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

Table 1: Voltage and current rating of H series IGBTs

Device selection	Techno/ series	Blocking voltage rating (V_{cesmax})	Current rating (I_c @ 100 °C)	Main benefits	Key product
Primary switches Q1, Q2, Q3 and Q4	Trench gate field-stop 'H' series	1200 V	15 A, 25 A, 40 A	• High switching speed • Low thermal resistance • Safe paralleling operation • Very fast recovery, anti-parallel diode • Minimized switching-off tail current • Positive $V_{ce(sat)}$ temperature coefficient	STGW(A)xxH120DF2

The saturation voltage $V_{ce(sat)}$ down to 2.1 V (typical, at nominal collector current and 100 °C) ensures minimal overall losses for higher efficiency operation at switching frequencies above 10 kHz.

Other key features of the new IGBTs include:

• Design extremely rugged with latch-up-free operation up to four times the nominal current, and minimum short-circuit withstand time of 5 µs at 150 °C starting junction temperature
• Extended maximum operating junction temperature of 175 °C for enhanced service lifetime and simplified cooling system
• Wide safe operating area (SOA) for greater reliability in applications where high power dissipation is required
• Excellent EMI characteristics thanks to a near ideal waveform during switching events
• Positive temperature coefficient of $V_{ce\,(sat)}$, with distribution of parameters from device-to-device, allowing a safer parallel operation in high-power applications

3 Welding machine electrical specifications

A 3-phase/7.5 kW IGBT advanced inverter technology MIG/MAG/MMA/CO2 Gas-shielded welder has been used as a test bench for the analysis performed with the 1200 V trench gate field-stop technology IGBTs, H series. This machine has high duty cycle, high efficiency, energy saving, stable performance and adjustable output current/voltage. The following table shows the related technical data.

Table 2: Technical data for welding machine

Welded process	CO2/MIG/MAG/MMA	
Rated supply voltage	3-phase AC 380 V ± 15%	
Frequency	50/60 Hz	
Rated input capacity	10.1 kVA	
Input current	15.4 A (max. value)	
	11.9 A (rms value)	
Output current adjustment range	CO2/MIG/MAG	50 A to 250 A
	MMA	50 A to 220 A
Output voltage range	CO2/MIG/MAG	16.5 V to 26.5 V
	MMA	22 V to 28.8 V
Output OCV	53 V	
Maximum duty cycle	CO2/MIG/MAG	60% at 26.5 V / 250 A
	100% at 23.7 V / 194 A	
	MMA	60% at 28.8 V / 220 A
		100% at 26.8 V / 170 A
Power factor (COS Φ)	0.95	
Efficiency	85 %	
Base metals	Low carbon steel, alloy steel and stainless steel	

Welding machines cannot be operated at their maximum current continuously therefore the "maximum duty cycle" is defined as the percentage of time in a 10 minute period during which a welder can be operated continuously at its rated output before overheating. However, the power supply is able to deliver more output current than the maximum for its rated duty cycle but for a shorter time. The control system monitors all the input/output variables and operator settings in order to dynamically adjust the output and maintain stable welding response in terms of CC (i.e. constant current power source with minimal current change for large output voltage variation) and/or CV (i.e. constant voltage power source when a big change in voltage leads to a large change in output current) characteristics against line and load changes.

Dynamic load variation response capabilities are required to follow rapidly the changes involved during the load transitions, due to the arc striking or during operations from open-circuit to short-circuit conditions *[6]*. Moreover, the system is also able to offer multi-process welding capabilities and automatically compensates variances which may occur during the welding sequence (i.e. fluctuation or irregularity in primary power such as voltage spikes and dips) and that can be reflected in the output parameters.

4 Description and analyses of H series IGBT test conditions

The STGWA40H120DF2 in TO-247 package long leads has been tested in the
3-phase/7.5 kW welding machine implementing the full-bridge converter configuration at
switching frequency of around 20 kHz.

The table below lists the main parameters of these components; for more details regarding
these IGBTs, please refer to the relevant datasheet available on www.st.com.

Table 3: STGWA40H120DF2 main parameters

Device	Package	BV_{ces}	I_c @ 100 °C	T_{j-max}	$V_{cesat(typ)}$
STGWA40H120DF2	TO-247	1200 V	40 A	175 °C	2.1 V

Four IGBTs have been connected each one to the four legs of the "full-bridge DC-DC
converter" configuration of the welding machine board tested in "free air" (open board
without housing or metal shroud) conditions with ambient temperature T_{AMB} = 25 °C
(+/- 2 °C).

Figure 2: "Full-bridge topology welding machine power converter section" shows the power
section of a typical full-bridge converter where diagonal pairs of switching devices are
operated simultaneously and in alternate sequence each other.

Figure 2: Full-bridge topology welding machine power converter section
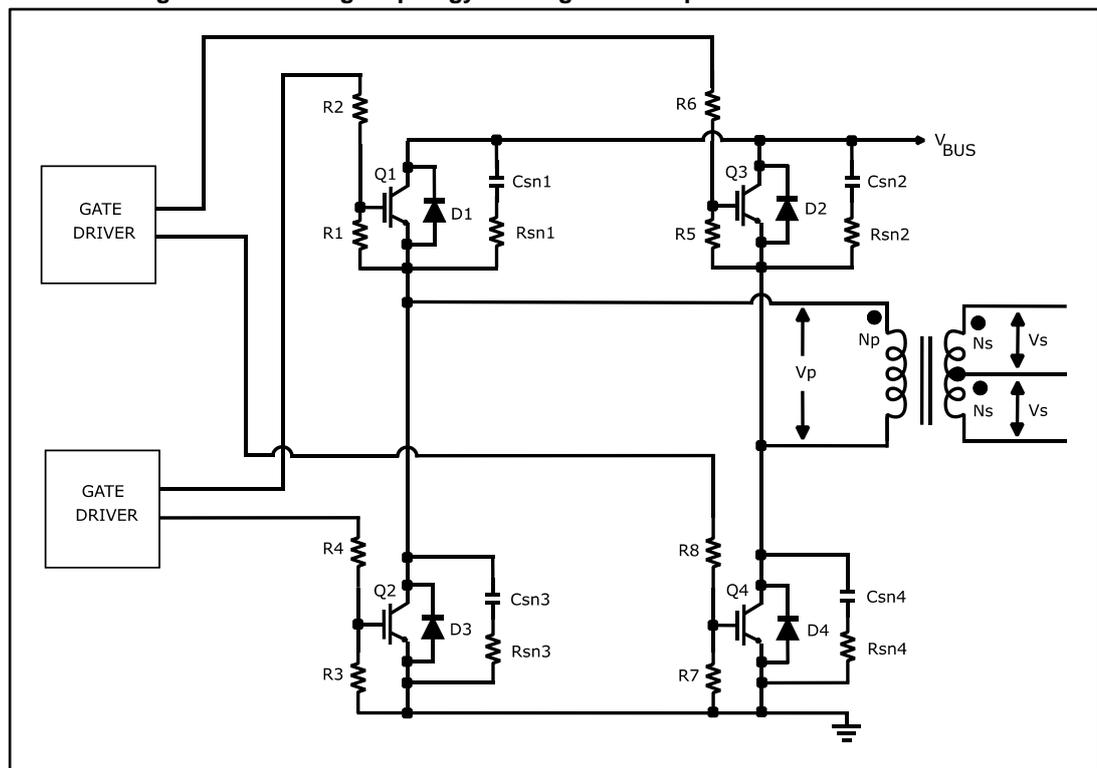
During the turn-on time of a couple of transistors, the primary winding current is made up of
reflected load current and magnetizing current for the transformer magnetic field. Duty

cycle control is implemented with symmetrical PWM for the two diagonals of IGBT transistors. The maximum allowed duty cycle D_{max} for the devices connected in this topology is as follows:

$$D_{MAX} = \frac{T_{ONmax}}{T} = 35\%$$

No diode is placed anti-parallel to each switch externally and the demagnetization current of the transformer flows through the integrated diode of the IGBT during the recirculation phase.

The switching performance and temperature characteristics of these devices have been evaluated at full load steady-state operation in "open board" conditions at room temperature (25 ºC). Besides, several operating conditions for the board by stepping the output current level up to 200 A, with 3-phase 380 VAC input mains and 50 Hz frequency have been considered.

In particular, analysis of the devices has been carried out under the following test conditions:

- Switching frequency fixed to ∼20 kHz
- Gate driving resistances R1, R3, R5, R7 = 10 kΩ and R2, R4, R6, R8 = 10 Ω
- RC snubber network with Rsn1, Rsn2 , Rsn3 , Rsn4 = 22 Ω and Csn1, Csn2, Csn3, Csn4 = 1 nF
- Output current variation ranging from 100 A up to 200 A
- Output load resistance ∼145 mΩ

In the analyses, the full load condition has been 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 has been used to maintain a constant temperature and therefore keep total resistance value constant. This external fan has been mounted away from the welding machine to avoid any influence on the thermal performance of the devices. Moreover, in all tests performed, the IGBTs have been screwed to the same heat sink 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 have been performed with the IGBTs connected with wires in order to allow the insertion of the current probes to record the signals. Under these conditions, the electrical behavior of parameters such as V_{CE} voltage across collector and emitter pins, the collector (or emitter) current IC and the V_{GE} voltage across gate and emitter pins during normal operations has been taken into account.

5 Overview of thermal and electrical measurements

In the following tables and graphs, electrical measurements are detailed for the total input power, input current (single phase), total output power, efficiency and power factor (PF) for each one phase line φ1, φ2, φ3 in conditions of balanced system as well as the temperature levels achieved by the STGWA40H120DF2 during the electro-thermal analysis carried out on the board. The application operating conditions (3-phase 380 VAC, 50 Hz input) are:

- Full load steady-state operation at 100 A output current
- Full load steady-state operation at 150 A output current
- Full load steady-state operation at 200 A output current

Below results achieved by the STGWA40H120DF2, tested on a 7.5 kW welder. The case temperature measurements have been taken by a thermal-camera once thermal stability has been achieved by the devices running on the board.

Table 4: STGWA40H120DF2 thermal and electrical measurements

Device	Output current (A)	Input power [W]	Input current [A]	PF	Output power [W]	Efficiency [%]	Temp [°C]
STGWA40H120DF2	100	1980	~3.8	0.78	1562	~79	~ 50
	150	4100	~7.1	0.88	3456	~84	~ 69
	200	6876	~11.3	0.92	5840	~85	~ 90

The measurement of the turn-off energies and total power losses (by neglecting the turn-on power losses) for a single IGBT of the full-bridge configuration are indicated in the tables and graphs below, starting from 100 A up to 200 A output current for a 3-phase 380 VAC input mains at 50 Hz.

**Table 5: STGWA40H120DF2 turn-off energies vs load current**

Device	Eoff @ 100A [µJ]	Eoff @ 150A [µJ]	Eoff @ 200A [µJ]
STGWA40H120DF2	~251	~493	~888

Table 6: STGWA40H120DF2 total power losses vs load current

| Device	Output current (A)	Conduction power losses [W]	Turn-off switching power losses [W]	Total power losses [W]
STGWA40H120DF2	100	~ 3.6	~ 5.0	~ 8.7
	150	~ 8.5	~ 9.9	~ 18.3
	200	~ 14.9	~ 17.8	~ 32.7

The plot of turn-off energies as a function of the load current is shown below in *Figure 3: "STGWA40H120DF2 turn-off energies vs load current @ 3-phase 380 VAC"*.

Figure 3: STGWA40H120DF2 turn-off energies vs load current @ 3-phase 380 VAC
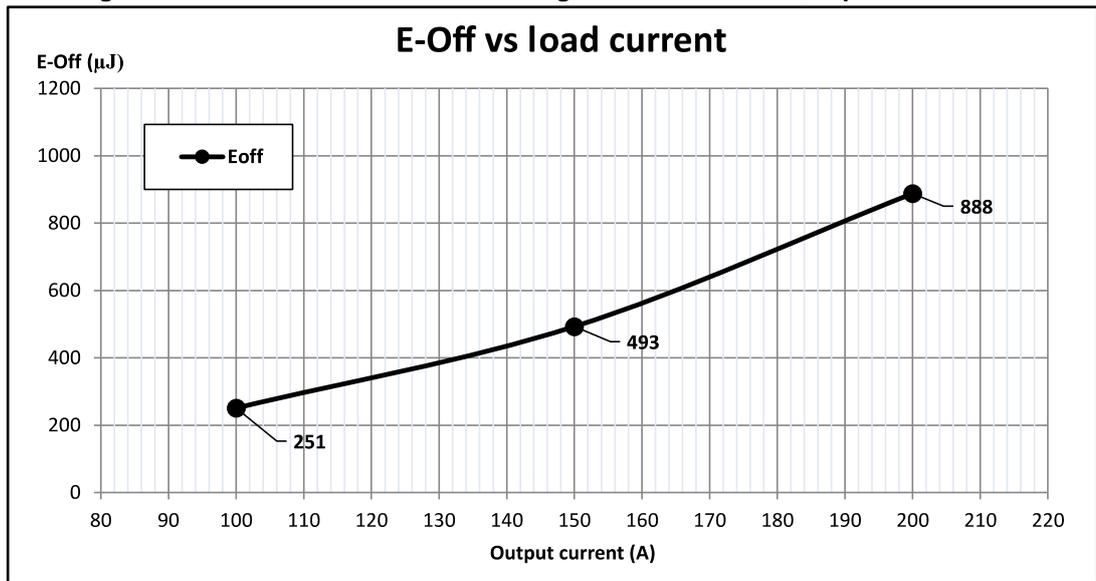
In the following *Figure 4: "STGWA40H120DF2 temperature and operating time at 3-phase 380 VAC"*, the primary axis shows plots of the total power losses (by neglecting the turn-on losses) while the secondary axis shows plots of the temperature reached by the devices under these same output current level conditions.

Figure 4: STGWA40H120DF2 temperature and operating time at 3-phase 380 VAC
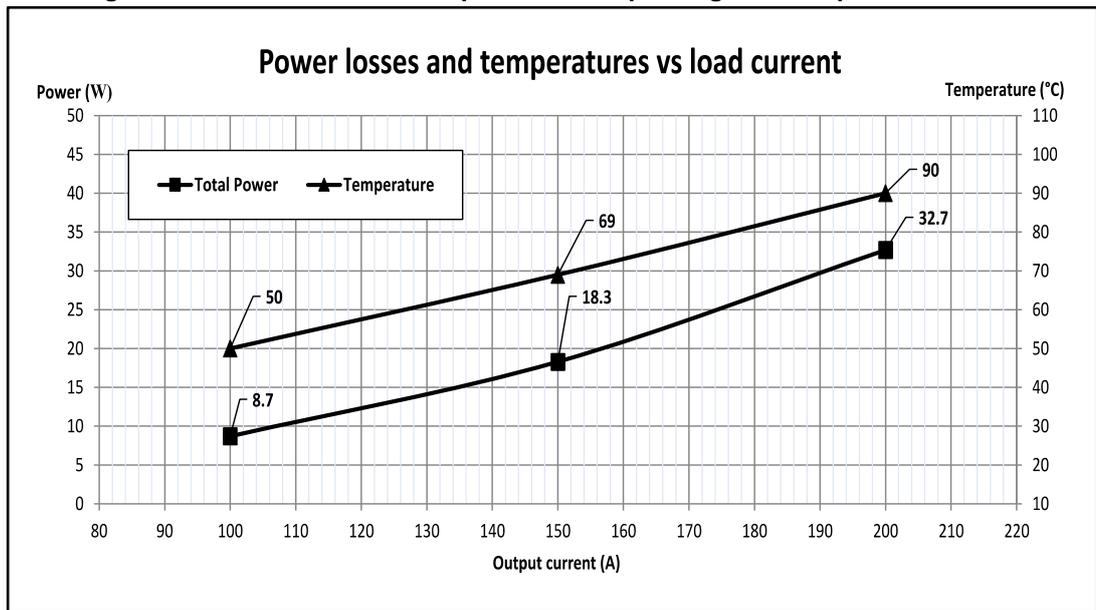
The STGWA40H120DF2 demonstrates highly satisfactory thermal behavior, achieving 90 °C approx. for 200 A output current. The overall electrical and power dissipation performance is very good for the tested IGBTs. These devices are able to switch with low amounts of turn-off energies in all different working conditions of the application, including the worst case maximum value of ~888 µJ for the turn-off switching at 200 A output load current.

6 Electrical analysis and waveforms

The signal waveforms and temperatures have been acquired and measured for the two devices Q1 and Q3 connected in the high-side part of the full-bridge converter configuration.

The acquired waveforms illustrate below the switching performance of the tested IGBTs.

Use the following color codes to understand the information:

- Q1 collector (or emitter) current: "IC1" signal in yellow
- Q3 collector (or emitter) current: "IC3" signal in dark blue
- Q1 collector-emitter voltage: "V_{CE1}" signal in red
- Output welding current: "I_{out}" signal in green
- Q1 instantaneous power (V_{CE1} x IC1): "Power" signal in orange

The figures below depict the signals of the high-side devices Q1 and Q3 of the IGBT STGWA40H120DF2 connected to the two full-bridge diagonals during the steady-state operation and switch-off phases varying the output current from 100 A to 200 A levels.

Figure 5: STGWA40H120DF2 (Q1 and Q3) @ 100 A output current
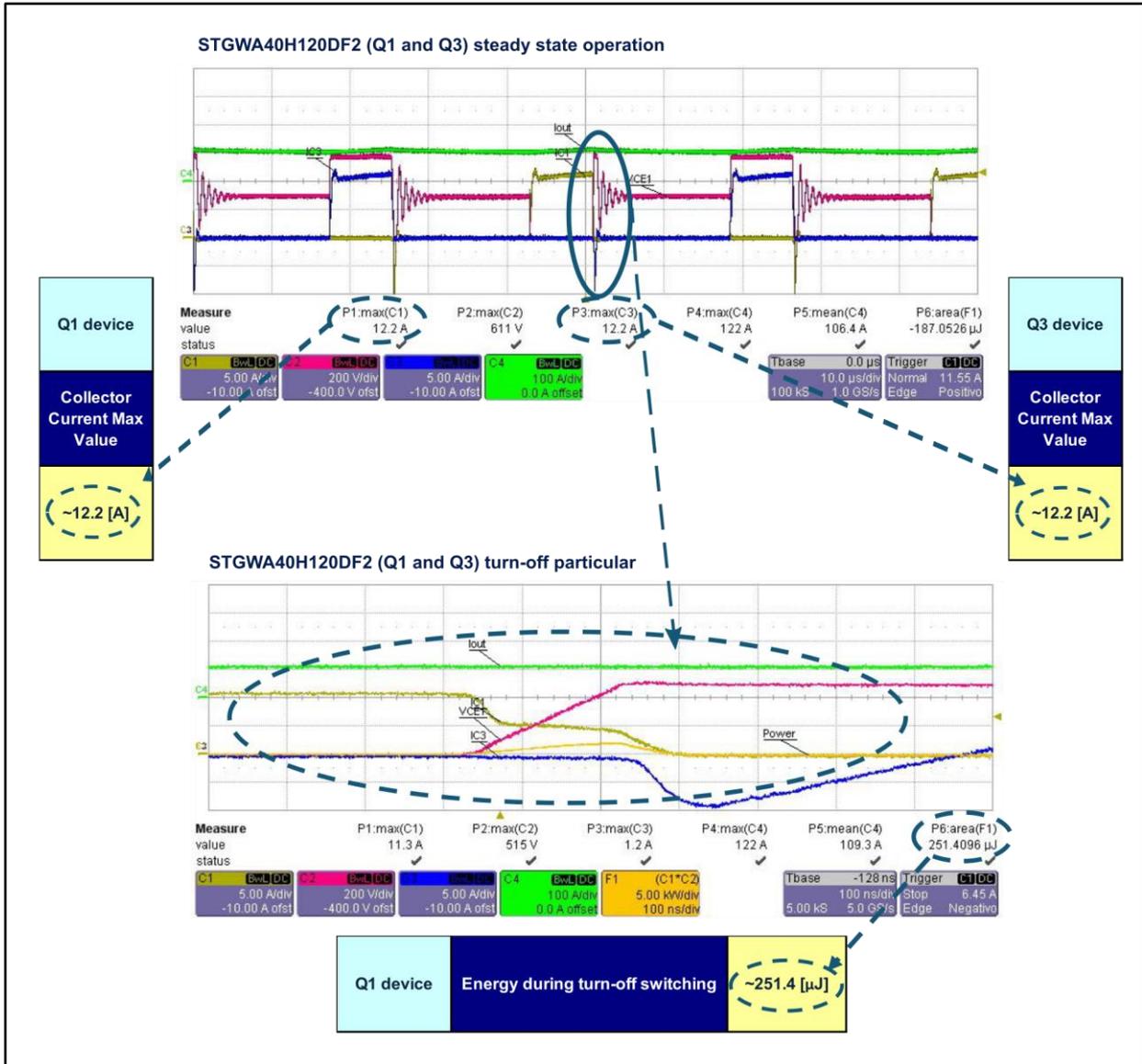
**Figure 6: STGWA40H120DF2 (Q1 and Q3) @ 150 A output current**
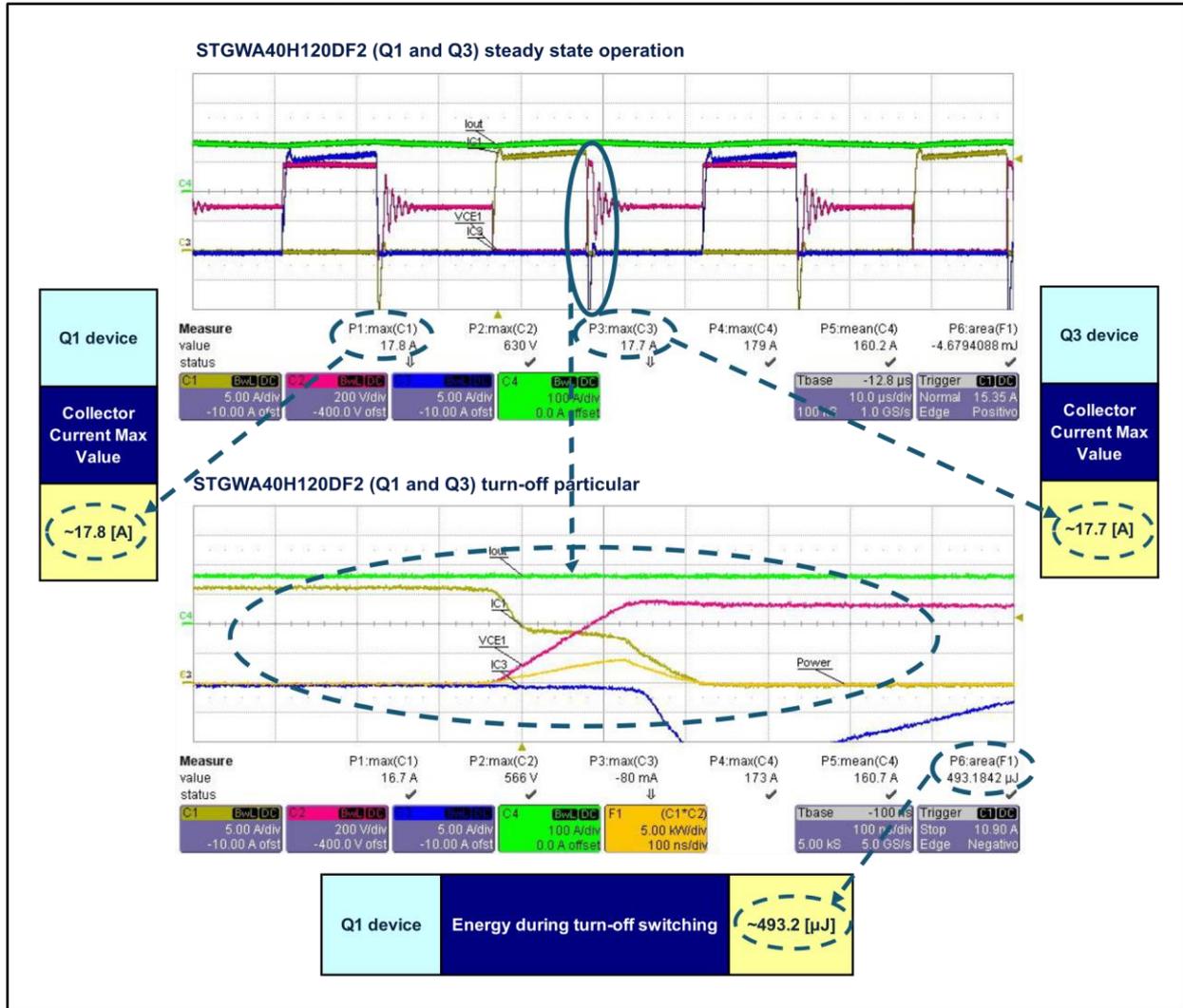
Figure 7: STGWA40H120DF2 (Q1 and Q3) @ 200 A output current
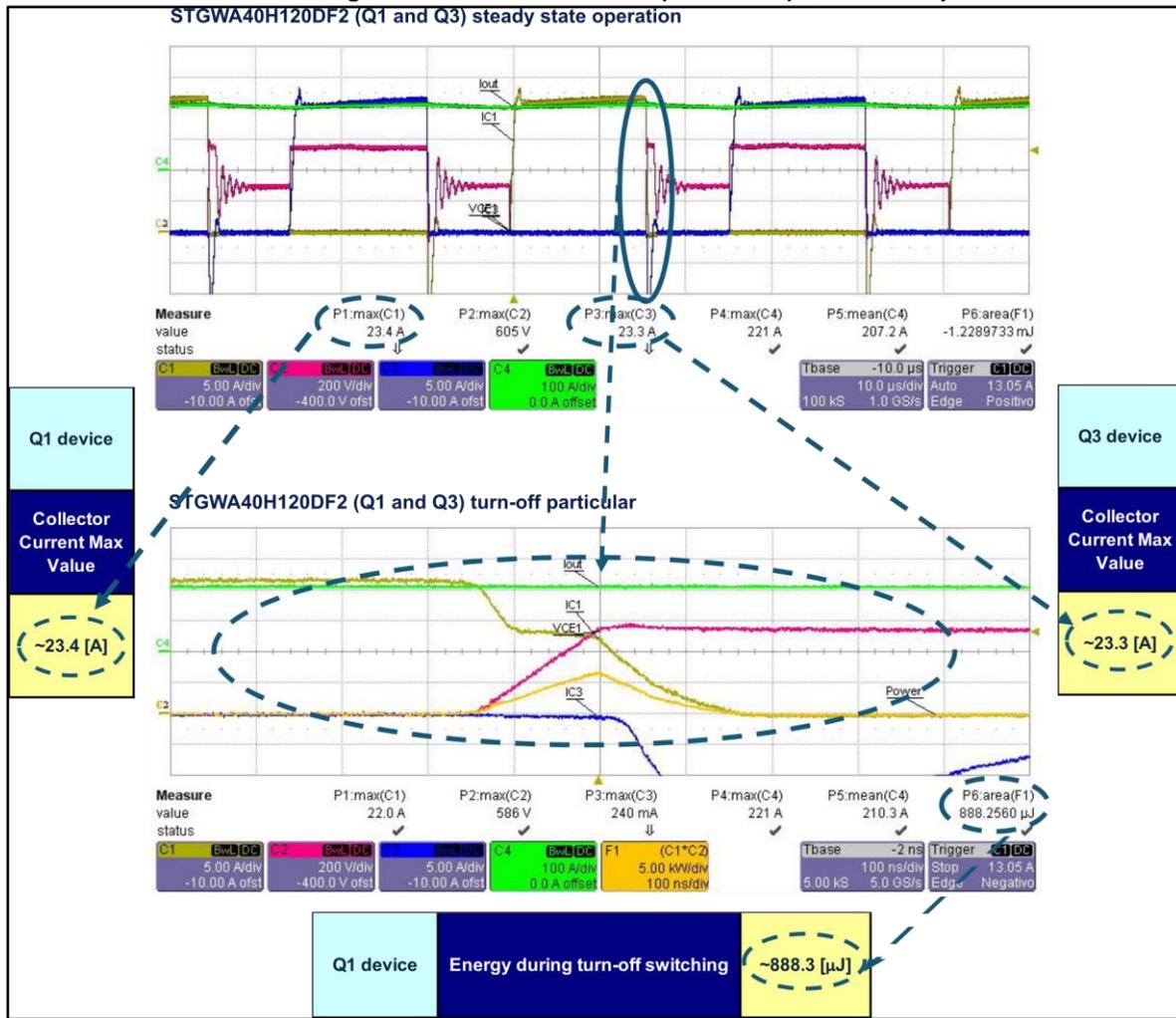
As it can be noticed, the IGBTs run on the board with a duty cycle equal to 32% during the conduction phase by reaching a peak current of around 23 A at the full load steady-state operation with 200 A output current.

7 Conclusion

Test results about the field-stop high-speed technology H series IGBTs, analyzed on full-bridge forward topology converters for welders have been presented. Very good performance of power dissipation and switching characteristics has been achieved in normal steady-state working conditions on 7.5 kW evaluation welding platforms, thanks to the ideal trade-off between $V_{ce(sat)}$ and E_{OFF} of these IGBTs. The STGWA40H120DF2 has showed high thermal performance with around 90 °C measured under a 200 A output current condition. The acquired waveforms clearly demonstrate a general good electrical performance of the H series IGBTs, with low turn-off energies for the 3-phase 7.5 kW welder system described above.

8 Bibliography

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Appendix A   Topology equations and the 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 VIN, 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 IC, max and IC,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

$$I_{C,ave,on} \geq \frac{P_{OUT}}{\eta \cdot V_{IN,min} \cdot 2 \cdot D_{MAX}}$$

Where

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

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

Figure 8: Full bridge topology

Figure 9: IGBT Collector current in CCM
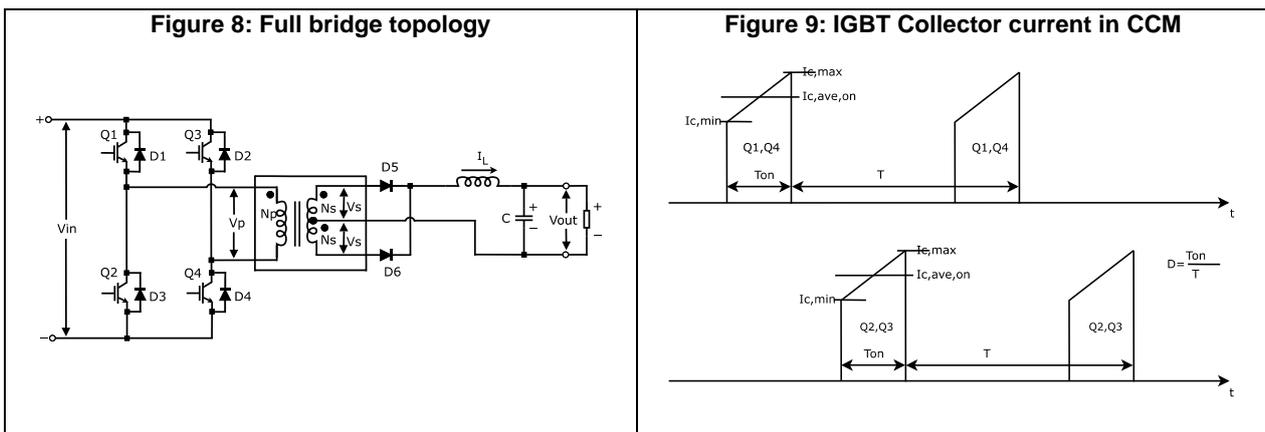
Setting the following electrical conditions at maximum input power operation for the 7.5 kW welder:

$$P_{IN} = \frac{P_{OUT}}{\eta} = 7.5kW$$

$$V_{IN,max} = \frac{3}{\pi} \cdot V_{mL} = \frac{3 \cdot \sqrt{3}}{\pi} \cdot V_m = \frac{3 \cdot \sqrt{3}}{\pi} \cdot \sqrt{2} \cdot 220 = 515V$$

$$D_{MAX} = \frac{T_{ONmax}}{T} = 35\%$$

$$\Delta I_{C,max} = 25\% \cdot I_{C,max}$$

Where $V_{mL} = \sqrt{3} \cdot V_m$ is the maximum line-to-line supply voltage and $V_m = \sqrt{2} \cdot V_{phase}$

is the maximum phase voltage.

Therefore, from the previous formulas, the maximum collector current for a single IGBT device mounted in a full bridge configuration for the 7.5 kW welder is given by the following equations:

$$I_{C,ave,on} = \frac{P_{OUT}}{\eta \cdot V_{IN,min} \cdot 2 \cdot D_{MAX}} = \frac{7500}{515 \cdot 2 \cdot 0.35} \cong 21A$$

$$I_{C,max} \geq I_{C,ave,on} + \frac{\Delta I_C}{2} = I_{C,ave,on} + \frac{0.2 \cdot I_{C,max}}{2} \quad \Rightarrow \quad I_{C,max} \geq \frac{2 \cdot I_{C,ave,on}}{1.75} \cong 24A$$

9 Revision history

Table 7: Document revision history

Date	Revision	Changes
25-Oct-2016	1	Initial release.

IMPORTANT NOTICE – PLEASE READ CAREFULLY