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APT9904

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APPLICATION NOTE

48kW RESONANT CONVERTER FOR X-RAY MACHINES USES HIGH SPEED POWER MODULES WITH INTEGRAL LIQUID COOLING

Presented at PCIM Europe 1999, Nürnberg Germany

8kW RESONANT CONVERTER FOR X-RAY MACHINES USES HIGH SPEED POWER MODULES WITH INTEGRAL LIQUID COOLING

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Abstract.

This paper describes an innovative method for the removal of heat from the four IGBT power modules equipping a 48kW ZVS-mode resonant power converter for CT X-ray machines. In this converter, output voltage is regulated between 80 and 140kV with 1% accuracy and low ripple, by varying the switching frequency from 48-68kHz. Even though switching losses are well below 1%, at these power levels large air-cooled heat sinks are needed to evacuate the heat. In installations where space is at a premium, water-cooling is a viable alternative. Traditionally, liquid cooling is implemented by bolting a power module onto a water-cooled heat exchanger. While more effective than air cooling, the arrangement is less than ideal, thanks to the thermal barrier between the module and its separate sink. This interface contributes significantly to the total junction-to-water thermal resistance. In APT's Integral Liquid Cooled (ILC) heat-exchanger concept there is no interface, because the module's baseplate doubles as the heat exchanger's lid. In this way, the cooling fluid is in direct contact with the module, and thermal resistance is dramatically reduced.

Introduction

The 48kW converter defined in this paper operates in continuous series resonance. Four independently packaged power modules, each containing two

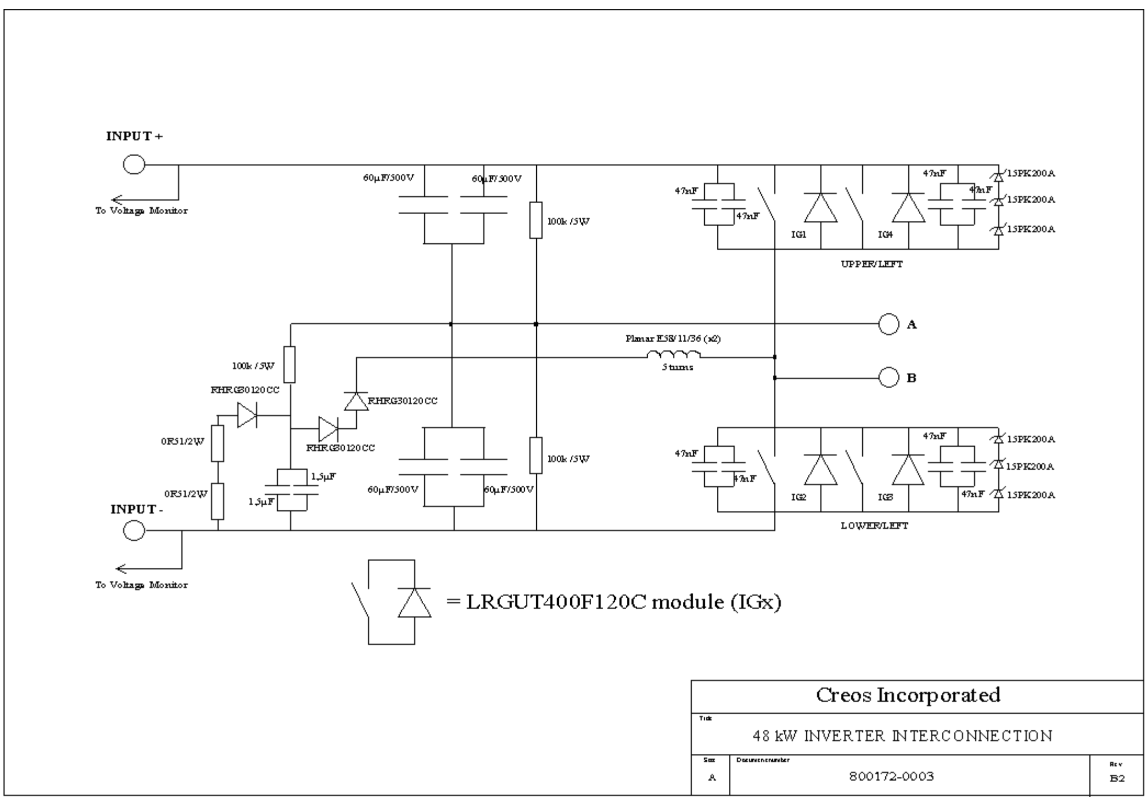

Figure 1 Inverter interconnections

paralleled IGBTs with antiparallel diodes, are arranged in either half bridge or push-pull topology, depending on whether the input is 400VAC or 200VAC. At maximum load, the peak current is 550A at 50kHz, giving 275A per module for 48kW out. The generator is zero-voltage switched to create a continuous series resonant output current. This current is transformer isolated, stepped up and rectified to the desired output level. The output voltage is regulated by a DSP-based frequency modulated controller, with dual loop feedback control on both resonant current and load kV.

To achieve a wide range of output power, the system operates from 48kHz up to 68kHz with a resonant LC shunt across the load transformer. While the basic series resonance is set to 48kHz, the shunt is fixed at 68kHz. At the lower end of the frequency spectrum the generator functions near resonance, and power throughput is high. As frequency increases, the overall impedance rises while the load is being shorted out by the resonant shunt. At 68kHz this corresponds to zero power. Figure 1 illustrates the power circuit on the primary side.

In state-of-the-art X-ray equipment, size reduction is a major goal. The four ZVS2 modules in this converter, with their tightly packed IGBT and FRED chips, require only ¼ of the surface area used in the previous generation of CREOS generators. The inclusion of drive isolation and ZVS control circuitry adds further

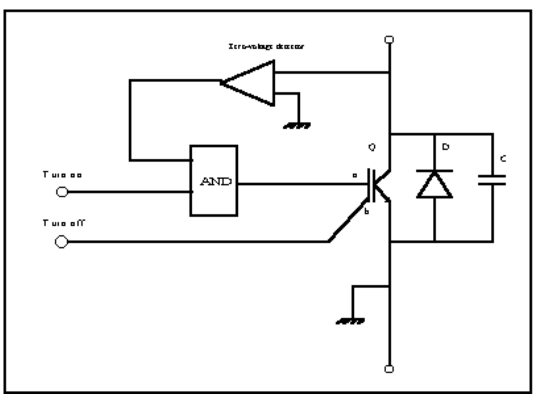

Figure 2 Functional diagram of Thyristor-dual

gains, to where the total area is only one sixth. As a bonus, control signals have less distance to travel, making for improved noise immunity and a more robust assembly.

There is, nevertheless, a downside. With the full semiconductor complement of the converter now concentrated inside four compact power modules, heat density is so high that thermal management is difficult. The heat exchangers are so big that they tend to dwarf the converter. To maintain a sink temperature of 50°C in the air-cooled version of this generator, the heatsink is an enormous 50cm x 40cm x 10cm aluminium extrusion, blown with forced air! The equivalent ILC module, on the other hand, with its vastly improved thermal characteristics compared to either air- or conventional liquid-cooled type, is little bigger than the bare air-cooled module minus its sink. Because the water chamber is galvanically isolated from the electrical circuit, plumbing is straightforward. Individual modules are piped either in series or in parallel for direct connection to the water mains, or to a self-contained recirculation system.

ZVS phase-leg, with spontaneous turn-on and switched turn-off

The advent of IGBTs and power MOSFETs has opened new perspectives for advanced converter topologies. In particular, detailed study of commutation mechanisms has led to a greater recognition of the merits of “soft switching”, with its much improved performance at higher frequencies. One of the most interesting of these developments is the “thyristor-dual”, an artificially synthesized switch (Figure 2) combining the spontaneous loss-free turn-on of a diode with the gate-controlled turn-off of a real switch. Thyristor-duals are generally configured as phase legs for use in voltage-fed inverters. They are created practically by connecting a semiconductor switch that can be turned off (BJT, IGBT, MOSFET etc.) in antiparallel with a diode and an all-important snubber capacitor. There is also an AND gate, that allows turn-on only when zero-voltage and turn-on validation concur. In both Figure 2 and its phase leg equivalent of Figure 3, the two switches and their related variables are defined by the subscripts 1 and 2.

In Figure 3, VK1 is the voltage across K1, I_{CH} the alternating current to the load. K1 and K2 are gate signals to the switches. For simplicity, I_{CH} is shown as a sinewave, but this is not restrictive, since only the position of its zero points with respect to the gate signals is important.

Starting from time to in Figure 3, the following sequence occurs:
At t= t_0: VK1=E and VK2=0, corresponding to K1 OFF and K2 ON. With I_{CH} positive, D2 conducts. Because VK2 = 0, T2 is validated. At t=t_1: I_{CH} changes sign and T2 conducts. At t=t_2: T2 turns off, I_{CH} transfers to C1/C2, VK2 rises and VK1 falls. At t=t_3: D1 conducts, VK1=0 and T1 is validated. At t=t_4: I_{CH} changes sign and T1 conducts. The sequence is

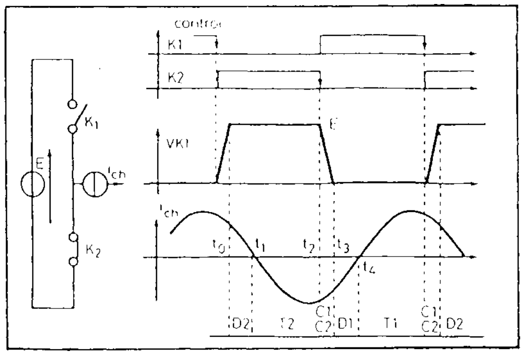

Figure 3 Waveforms and control signals

completed when T1 transfers to D2 in the same manner as T2 to D1.

It is important to recognize that this operating mode always prevents shoot-through in the branch. Firstly, the turn-on signal to any one switch is only validated when the voltage across its complement is E. This implies that the latter must be solidly "off" before the former can turn on. Secondly, the provision of snubbers to slow down reapplied dv/dt. Too-high reapplied dv/dt following device turn-off can provoke current shoot-through, as Miller-coupled charge tries to turn the device back on again. A fringe benefit is that this logic obviates the need for built-in "dead-time", reducing cost of the drive circuits.

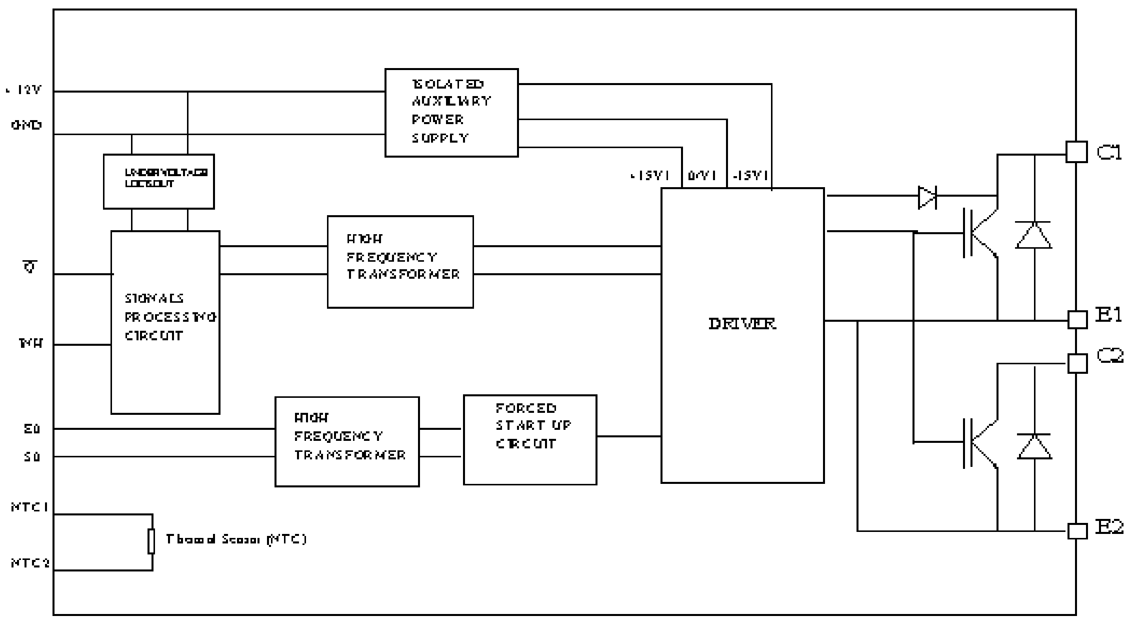

Figure 4 LRGUT400F120C

Here, as in all topologies employing turn-off switches with shunt capacitive snubbers, the turn-off process is accompanied by energy exchange between load and capacitors, since load current charges the capacitors as the switch voltage rises. In a DC chopper or PWM inverter this energy is lost as heat in the RCD snubber during switch turn-on. In the thyristor-dual, on the other hand, since it is load current flowing in the capacitors as the switch voltage collapses, the energy is returned to the load. Because such a snubber is virtually loss-free, its capacitor value can be increased as required to minimize turn-off losses in the switch. In this configuration, turn-on losses are of course negligible, thanks to the spontaneous turn-on.

The LRGUT400F120C Power Module

APT Europe, in collaboration with CREOS Incorporated in the USA, has engineered a 1200V/400A custom power module for use in the 48kW X-ray generator just described. Configured as a single switch to operate in the ZVS dual-thyristor mode, each module contains 1200V rated IGBTs and matched antiparallel diodes, as well as the logic circuitry necessary to provide full ZVS functionality. Two modules are paralleled for the high side and two for the low side of the half-bridge converter phase leg. The block diagram is portrayed in Figure 4.

Galvanically isolated driver circuits are positioned close to the power switches for best performance. Control signals are isolated via high frequency transformers, which enhance electrical performance and boost reliability. An auxiliary +/- 12 V internal power supply is incorporated to drive the IGBTs.

A single 12V supply on the primary side is all that is required for full CMOS control-logic compatibility.

Special start-up circuitry ensures that the system will power-up properly when voltage is applied. While the efficiency of a ZVS converter like this is unmatched at high frequencies, dissipation in the modules is still significant, given their compact nature and the high power throughput. For maximum throughput with modest junction temperatures, all power semiconductor chips are mounted on aluminium nitride substrates for best thermal conductivity.

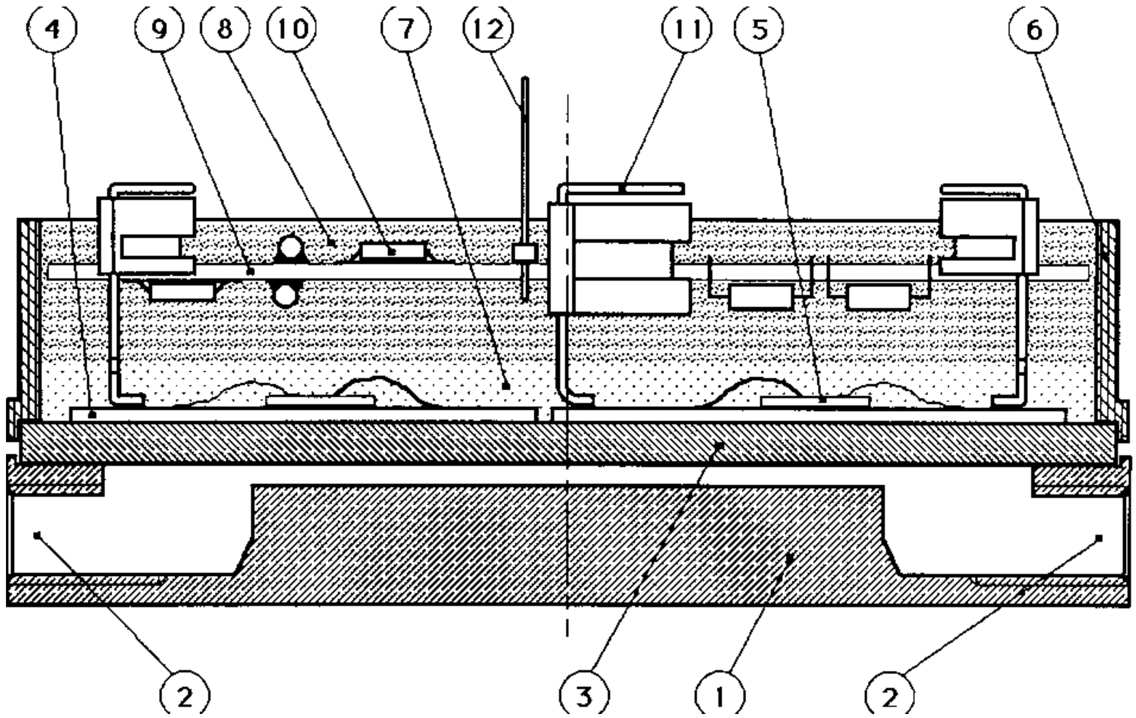

Figure 5 Integral Liquid Cooled Module

The driver output stages, implemented with a blend of SMDs and silicon chips, are directly mounted on the ceramic substrate alongside the power devices. Control and isolation circuits are grouped on a separate four layer PCB, one layer of which is a ground plane for guaranteed noise immunity.

Power connections are M5 screws, with logic level and auxiliary supply circuits interfaced through 0.6 mm x 0.6 mm pins on a 0.1" raster. This arrangement allows direct mounting of the control board without wire links. In this way, parasitics are minimized and reproducibility assured over long production runs.

Two versions of this module have now been produced, a conventional baseplate-equipped type for air-cooled installations, plus its more recent and revolutionary ILC (integral liquid cooled) sibling -------

ILC Challenge

- To engineer the lowest possible thermal resistance between semiconductors and ambient.
  In the ILC module, there is no case-to-sink interface, a significant part of the whole in a run-of-the-mill classic design.
- To eliminate the need for costly surface finishing of the baseplate and its matching sink, without which interface thermals are poor and inconsistent. Likewise the need for messy thermal grease.
  In the ILC, there are no surfaces to machine or to “fill” with grease. The absence of mountdown-induced stress also means that in some instances the baseplate can be thinner, yielding lower Rth.
- Galvanic isolation, circuit to water.
  Because the internals of most power modules are laid-out on metalized ceramic substrates, their baseplates are isolated by default. Since the ILC is basically a standard module soldered to a “top-less” water jacket, it too is isolated. As a result, cooling water is not in electrical contact with the circuit being cooled, so there is no galvanic erosion to destroy the plumbing. The electrically isolated modules can be plumbed directly to the water mains if desired, without the need for costly dedicated cooling systems.
- Recyclable parts.
  An ILC module is conceived such that, in the event of (unlikely!) electrical failure, its relatively

expensive water jackets may be detached for eventual re-use.

ILC Construction

Figure 5 is the cross sectional view of a typical ILC module:

(1) Water chamber body: machined from solid copper stock, nickel-plated for long term protection.

(2) Inlet and exit coolant connections: threaded as required to suit the market area served.

(3) Module baseplate, doubling as water chamber cover: its thickness is chosen to suit the coolant working pressure (maximum 10 -12 bars). Attached to the water jacket by soldering, or by a combination of soldering and machine screws in extreme-pressure applications. Can be fabricated from “matrix-metal”, an AlSiC alloy having a thermal coefficient of expansion close to that of ceramic substrate materials. If materials having dissimilar coefficients are mated, the assembly is vulnerable to thermal fatigue-induced disintegration.

(4) Ceramic substrate, soldered to the baseplate: either aluminium oxide (Al_2O_3) or aluminium nitride (AlN). AlN, with superior thermal conductivity, is better performing. Al_2O_3 is more appropriate when low cost is critical. Metallized as required - either by thick film deposition or screening/etching in the case of DBC (direct bonded copper) substrates.

(5) Silicon chips and other power components, soldered to the substrate: upper connections to chips via ultrasonically bonded aluminium wires. Power switch drivers sometimes added.

(6) Moulded outer wall.

(7), (8) Silicone gel conformal coating over substrate assembly, with resin top layer to fill the cavity.

(9), (10) Internal PCB, with all necessary control and protection functions: hybrid SMD/chip construction.

(11) Power circuit connections: M5 or M6 screw-terminals, or equivalent to suit the application.

Performance

The benefits of liquid cooling are best judged by comparing the usable performance of an air-cooled power module to that of the same module in ILC form. The type chosen is the MU20M4, a 200V/ 4 mΩ single switch MOSFET rated for 470A at 25°C. This product is destined for use in motor control, welding equipment, and DC to DC converters. One of these

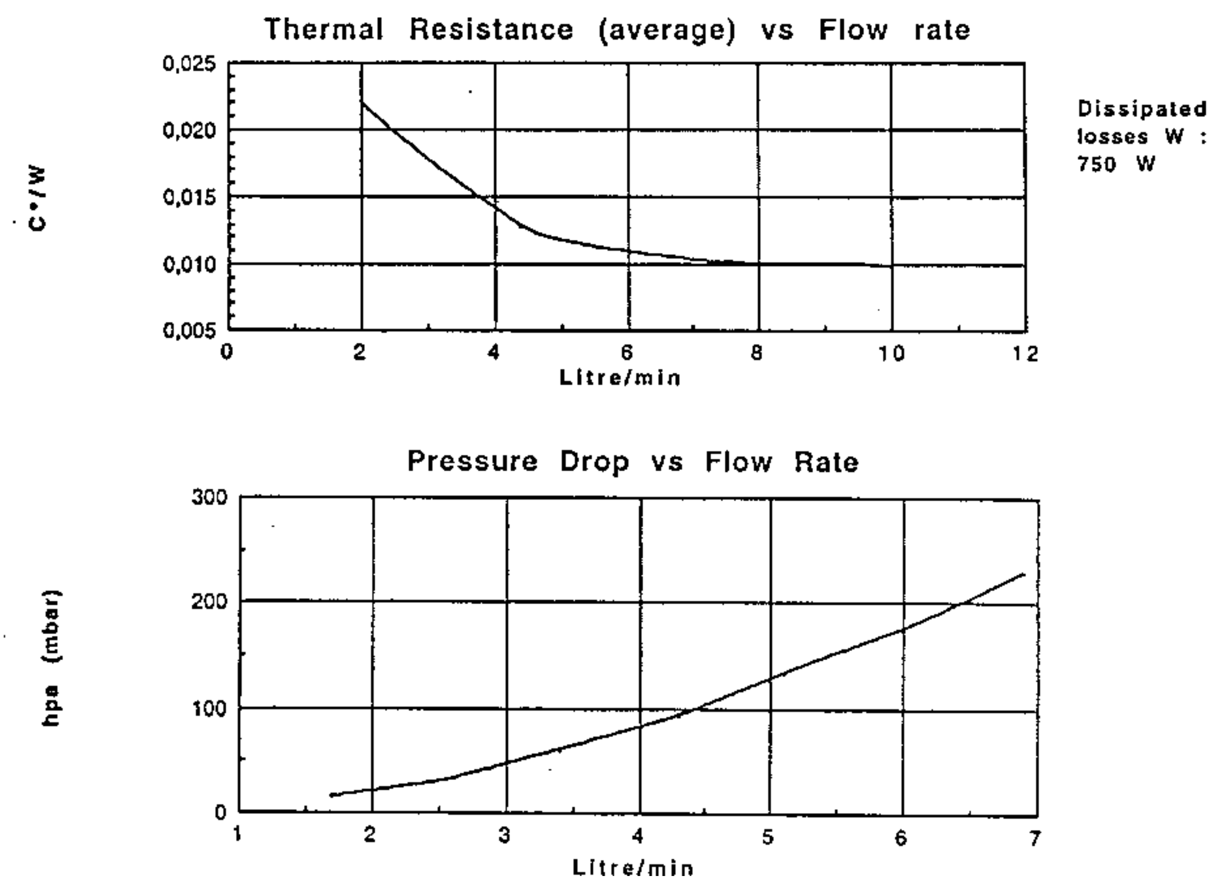

Figure 6 MU20M4-ILC Thermal Performance

modules is attached to a 160mm long Schaffner WA960 convection-cooled aluminium extrusion, Rth_{sa} = 0.2K/W. The liquid-cooled version, MU20M4-ILC, is the same module soldered to an ILC water jacket. In this case, thermal resistance depends on flow rate as shown in Figure 6. From this curve, <u>average</u> thermal resistance at a flow rate of 2 litres per minute is O.O22K/W, but for calculation purposes the <u>maximum-limit</u> of Rth_{cl} = 0.03K/W is used.

T_a (air or liquid) = 25°C, and T_j max = 150°C.

The thermal paths can now be established:

Chip Case Heatsink Air
x ---------------------- x ---------------------- x -------------------- x
Rth_{jc} = 0.07K/W Rth_{cs} = 0.05K/W Rth_{sa} = 0.2K/W

Chip Case Liquid
x ---------------------- x ------ --------------- x
Rth_{jc} = 0.07K/W Rth_{cl} = 0.03K/W

For air-cooling: $(T_j - T_a) = (Rth_{jc} + Rth_{cs} + Rth_{sa}) * P_D$, whence $P_D = (T_j - T_a) / (Rth_{jc} + Rth_{cs} + Rth_{sa})$

substituting: $P_D = (150 - 25) / (0.07 + 0.05 + 0.2) = 390W$

For liquid-cooling: $(T_j - T_l) = (Rth_{jc} + Rth_{cl}) * P_D$, whence $P_D = (T_j - T_l) / (Rth_{jc} + Rth_{cl})$

substituting: $P_D = (150 - 25) / (0.07 + 0.03) = 1250W$

Since: $P_D = I_D^2 * RDS_{on}$

And: RDS_{on} @150°C =2.1x RDS_{on}@ 25°C.

For air: $I_D = \sqrt{}\,(390 / 2.1 * 0.004)$ = **215A**

For liquid: $I_D = \sqrt{}\,(1250 / 2.1 * 0.004)$ = **386A**

Since I_D max = 470A @ 25°C

With air, percent usable capacity: I_D / I_{DMAX} = 215 / 470 **= 46%**

With liquid, percent usable capacity: I_D / I_{DMAX} = 386 / 470 **= 82%**

<u>Conclusions</u>

It has been shown that a series resonant half-bridge inverter, based on IGBT equipped ZVS "thyristor-dual" power modules, can output nearly 50kW DC in a state-of-the-art CT X-ray generator application. With the inverter frequency modulated at 48-68kHz for good magnetics utilization, switching losses are less than 1%, with output regulation likewise less than 1% over the range 80-140 kV. Ripple is an incredibly low 180V p-t-p below 1kHz.

It has also been demonstrated that the conversion of a conventional air-cooled power module into an ILC sibling, by grafting on a simple "topless" water jacket, can boost <u>realizable</u> output by 80%, when compared to an air-cooled equivalent. This improvement is due to the much lower junction-to-ambient thermal resistance of the ILC design. An additional benefit is the dramatic reduction in size, particularly sought after in space-conscious applications like X-ray generators. Plumbing is simplified by the galvanic isolation between circuit and sink.

If the ILC module baseplate is fabricated from a metal-matrix material, with thermal expansion similar to ceramic, the result is a product particularly suitable for applications like welding, where premature failures caused by thermal cycling often limit the lifetime of copper-based designs.

In applications like very high power X-ray generators, where space is at a premium, an ILC system is much more compact and easy to manage than an equivalent air-cooled design.

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Printed - December 1999