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Modern Technologies for Cooling Power Electronic Converters

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***Abstract*— Semiconductor elements such as MOSFET, GTO, IGBT, IGCT, etc. are now widely used in power converters for converting electrical energy. These converters find applications in power electronics, industrial drives, telecommunications, transportation, electrical network and many other applications. are realized by heat transfer and convection Cooling technologies are realized by heat transfer and convection. In applications that use natural or forced airborne cooling, with specific coolers – radiators provide effectively heat distribution to reduce the size and weight of the converters. A review of improved stepped radiator concept density of ribs for the purpose of achieving effective isothermally cooling. Where gravity can drive liquid flow, thermosyphons provide effective heat transfer to remote areas fin volumes that can be oriented for natural and/or forced airborne cooling. Liquid cold plates (Liquid Cold Plates LCP) offer means of cooling high thermal loads and thermal flows, including bilateral cooling for the highest density packaging. LCPs can be used in both single-phase cooling water or oil systems cooling liquids, as well as in two-phase cooling systems with dielectric and refrigeration fluids. New concepts were reviewed, including an air - cooled radiator cooling, thermosiphonic radiator, LCP with vortex flow and concept of direct contact cooling.**

***Keywords*— Semiconductor elements, MOSFET, GTO, IGBT, IGCT, thermosiphonic radiator.**

I. INTRODUCTION

The power electronic converters are vital for efficient generation, transmission and distribution, transformation and a huge variety of end uses of electricity. More cooling technologies are finding applications in power electronic converter cooling technologies to improve energy efficiency and reliability. Power electronic converters are used to improve the reliability and control of power systems [1]. The state of power electronic converters electronic converters and future trends in their development are discussed in [2, 3]. Silicon is a basic material for power semiconductor elements and to avoid device failure because of the effective cooling is crucial. On Fig. 1 shows the relationship the maximum safe operating temperatures depending on the voltage applied to the silicon crystal of the semiconductor element [2]. To expand the applications and achieve higher reliability, recently, semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) Their advantage is stable and reliable operation of the converters at high temperatures. However, the technologies used, passive and peripheral components, soldering materials, reliability and cost considerations currently limit transition temperatures up to ~ 175°C [4]. The maximum safe transition temperatures in SiC can exceed 300ºC [5], so even at high ambient temperatures environment can be provided enough cooling from smaller and cheaper radiators, which leads to further reduction of the dimensions of the converters with higher power.

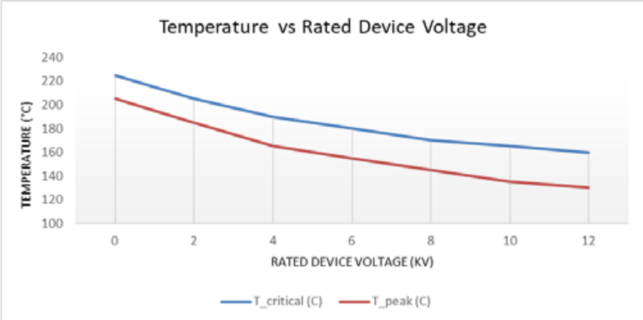

Fig. 1. Graphical dependence of the maximum temperature on the applied voltage

II. RESEARCH AND ANALYSIS

Thermal management solutions used for electronic cooling modules in automotive applications are reviewed. applications [6, 7]. The cooling liquid in such applications is available at temperatures above 100ºC, so cooling should be done with low temperature difference between semiconductor and cooling liquid. Very highly integrated cooling solutions are presented in [6], focusing on thermal management challenges in power converters. Similar cooling concepts can also be applied to other applications such as industrial drives, wind converters energy, HVDC power transmission, etc., depending on the constraints of each application. Various packaging designs and cooling solutions to reduce thermal resistance of high-power modules are described and compared in [8]. In microchannel liquid cold plates [9, 10] heat resistance to cold plates can be reduced to such degree that the internal thermal resistance of the electronic package to be made dominant thermal resistance. Phase change of cooling by forced convection boiling of refrigerant agent in cold weather plates is described in [11], including the more isothermal operation, which comes from using the latent heat rather than the sensible heat of the cooling medium liquid to provide cooling effect.

Cooling solutions in use today include:

1. About coolers with natural and forced convection airborne cooling
2. One-sided and two-sided liquid cooling cold plates
3. Microchannel liquid coolers built into main power supply plates module or integrated with the DBC substrate
4. Jet blow and direct contact liquid cooling of main module plates or DBC substrates
5. Two-phase liquid cold dielectric boiling plates refrigerated agent

Except for underwater or marine applications, the heat removed from electronic systems, ultimately. The heat is dissipated into the air. Air - cooled radiator systems cooling distracts the heat directly into the air that passes through the system by natural or forced convection. Systems that use liquid cooling, transfer heat from the electronics to the liquid, which in turn transfers heat to the air in a heat exchanger liquid-air like automotive radiator. In two-phase systems the heat from the power plant electronics transform liquid into vapor by boiling or evaporation and then the vapor returns to liquid phase when it transfers heat to the air in an air - cooled condenser cooling.

We have been looked at. some of the existing cooling solutions and presents new concepts for air - cooled radiators cooling, contour thermosiphonic radiator, liquid cold plate and concept for direct liquid cooling.

In Fig.2 is shown two common one's power semiconductor devices used for power modules. The IGBT module on the left typically used in applications below 6.5kV and has one flat surface for " one-sided " cooling. The other module is very suitable for stacking consistently for high- performance applications voltage and provides both upper and lower surface for "double-sided" cooling. Both modules are designed to be mechanically bolted to radiators or liquid cold plates.

Fig. 2. IGBT packages for single-sided and double-sided cooling

The interest in hybrids road and rail applications in recent years has led to personalized solutions with two-sided cooling from Alstom [12], Denso [13] and others, these modules are shown in Figure 3.

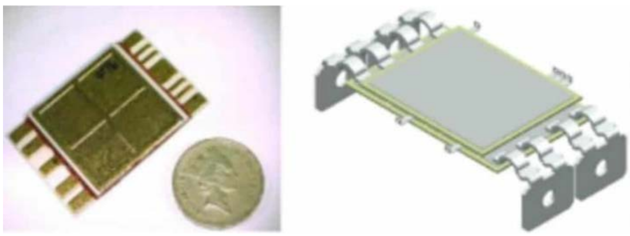

Fig. 3. Personalized power supply modules for duplex cooling

When designing power electronic converters for medium and high power, forced-air coolers are used airborne cooling.

Table 1 gives the values for thermal resistances along the path from the IGBT dies to the air for the aluminium forced - air radiator airborne cooling, illustrated the heatsink base measures 236 x 230 mm and cools one economy-pack IGBT module (162 x 122 mm) with a DBC substrate soldered to a copper 3 mm thick heat dissipation base. The aluminium fins are pressed into grooves in the aluminium The IGBT module is mounted on the heat sink using thermal paste to reduce re- existence of the thermal interface. The air flow through the heat sink is 0.25 m^3/s at 25ºC and 1 Bar, and the IGBT dissipates total 2kW of heat.

TABLE I
APPROXIMATE THERMAL RESISTANCES IN AN IGBT MODULE WITH AIR COOLING

Stack-up layer	Thickness (mm)	Resistance (°C/kW)	Resistance Percentage of total
Silicon	0.2	0.6	1.3%
Silver	0.1	0.2	0.4%
Copper	0.3	0.2	0.5%
Al-Oxide	0.38	4.0	9.7%
Copper	0.3	0.2	0.4%
Solder	0.1	0.6	1.3%
Copper base plate	3	0.7	1.6%
Thermal Paste	0.05	4.2	10.0%
HS-Base spreading	20	12	28.9%
HS-Fins convective	110	19	45.8%
Total		**41.5**	**100%**

The data show that almost 30% of the thermal resistance is due to ineffective heat distribution in the base. In Figure 4 is shown example of a cooler with copper basis for improving heat distribution heat flow. For the same configuration as copper base would allow a ~40% reduction in the scattering resistance in Table 1 from 12ºC/kW to 7ºC/kW or 10ºC decrease in transition temperature.

The values in Table 1 shows that the layer solder, copper main plate and pasta constitute 50% of the thermal resistance that is not connected to the radiator. This is even more important with liquid cooling, where the resistance of the liquid cold plate is ~0.1 to 0.2 times larger than an air - cooled radiator cooling.

Figure 4. Illustration of an IGBT module attached to an aluminium press with forced airborne cooling sink.

Fig. 4. Air-cooled radiator with copper base

Fig. 5 shows radiator with heat sinks pipes embedded in the aluminium basis. Thermal copper water pipes use copper powder and are embedded in the base using high - performance technology Acavid contact. Thermal pipes are oriented towards the radiators to level temperature gradient front to back because of air heating. A ~60% reduction in thermal resistance can be achieved with value up to 5ºC/kW or 14ºC reducing the transition temperature. The better heat distribution with heat exchangers pipes is achieved at a lower radiator mass compared to using copper basis. The last advances in the use of carbon nanotubes saturated on copper mesh and powder wick, allow thermal fluxes above 500 W/cm^2 [15] and a reduction in thermal resistance. Such is expected nanotechnology to be available in stores products on based on market requirements.

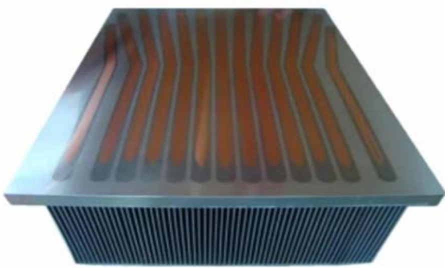

Fig. 5. Air cooling radiator with heat sinks pipes embedded in aluminium basis

Additional progress in the radiator 's performance is achieved if the connection based on ribs replaced with metallurgical a joint made by soldering or brazing the ribs to the base. This reduces thermal resistance with ~4ºC/kW, which allows additionally reducing the junction temperature by ~8ºC. Both radiators, shown in figures 5 and 6, include such improved base for connecting the ribs.

Recent The innovation consists in a radiator design with fin density increasing in the direction of flow, as shown in Fig. 8. The surface area of the radiators is lowest in the upper region where the cold air enters the radiator and increases gradually to the downstream area, until. The air is heated. In this way, the base of the radiator can be kept more isothermal, so that power modules mounted at different distances from the edge where it enters the air, to be able to cool down to similar temperatures. In addition, the general pressure drops across the radiator, and the total mass is reduced due to the lower density of fins at the top of the chain. This type designs the produced by gluing or soldering the fins to the base.

In the case of When it is necessary to install a series of modules, contoured ones are recommended. thermosiphon air - cooled radiators cooling.

The discussed so far radiator concepts position the surface of the heat exchanger to the air in the physical space adjacent to the power supply module. Thermal pipes were used to extend the radiator fins of a certain distance from the base of the radiator, but when gravity can be used advantageous, two-phase thermosyphons can provide higher performance solution. The simplest thermosyphons are simply gravitational thermal wick tubes surface type groove. In this type design the steam flow in the pipe is in reverse direction of the fluid flow along the pipe wall. This limits the maximum power that can be transferred because of the entrainment of the liquid in the high-speed steam flow [16]. The contour thermosyphon avoids this limitation by transporting steam in one pipe and returns condensed liquid through another pipe.

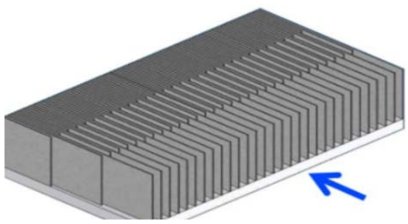

Fig. 6. Advanced radiator with rising density of ribs direction of the air stream

Fig. 6 shows radiator with air cooling, which uses contoured thermosyphon for transporting heat far into space outside power electronic the evaporator is equipped with an equal surface where it is mounted the power supply module and improved boiling surface from the inside to improve the heat dissipation ability flow and to decrease thermal resistance. The air - cooled capacitor cooling is similar to a car flow radiator steam inside extruded flat aluminium pipes and aluminium folded ribs outside the pipes to provide a large cooling surface area surface on the air side. The liquid in the thermosyphon evaporator absorbs the heat from the electronic module and passes into its steam The steam passes through the steam pipe to the condenser, where it rejects heat to the air and condenses back to liquid phase. Then the liquid condensate returns to the evaporator through the liquid return pipe to complete the cycle.

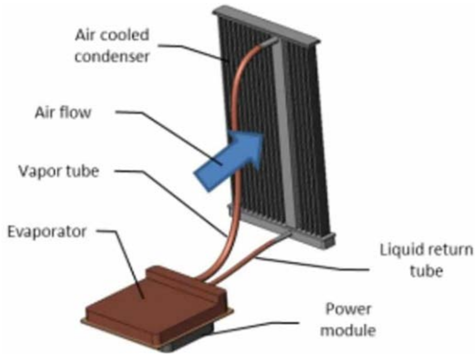

Fig. 7. Air cooling radiator using a contour thermosyphon

The thermal thermosyphon resistance radiator can be determined by using the heat transfer coefficient of boiling surface inside the evaporator according to figure 10 and condensation coefficient heat transfer of ~1 kW/m^2 -K inside the condenser tube. If a 122 x 162 mm IGBT dissipates 2 kW of heat, the thermal the flow on the evaporator wall is ~10 W/cm^2, and the boiling heat transfer coefficient is ~5.5 W/cm 2 -K. Including the thickness of the copper 3 mm thick wall, thermal the evaporator resistance is 1.3ºC/kW. Assuming that the air- cooled condenser cooling with a thickness of 230 x 230 mm by 30 mm and an air flow rate of 0.25 m^3/s (same as in table 1), the calculated thermal The capacitor resistance is 9.1ºC/kW, so the total thermally resistance R as is 10.4ºC/kW, which is about one third of the value of 31ºC/kW for the press - fin radiator studied in Table 1. This huge improvement in thermal characteristics comes with the extra's advantages of lower table, lower pressure drops and essentially isothermal radiator base for good static balance between the parallel IGBT matrices.

The main thing two - phase limitation contoured thermosyphon is that it is not suitable for moving platforms such as cars, where external forces on the body other than gravity can potentially displace the liquid from the evaporator and cause drying.

Since the working fluid inside the thermosyphon is a dielectric, in principle the power one a semiconductor can be submerged inside the liquid in the thermosyphon. Fig. 11 shows thermosiphon prototype radiator based on this type of concept of "immersive " cooling" [17]. Periodic two-phase thermosyphons can transport heat against gravity, using steam pressure to drive the flow [18].

In liquid systems cooling the liquid cold plates provide localized power plant cooling electronics by transferring heat to a fluid, which then flows to a remote heat exchanger and dissipates the heat in the air or to another liquid in secondary cooling system. The liquid cold plates provide more effectively cooling and allow higher levels of integration and significantly reducing the volume and weight of power systems electronics. Liquid cold plates type pipe and fin for cooling with DBC substrates with and without copper basic plates.

1. The liquid flow passes through ribs formed directly on copper and AlSiC basic plates.

2. One-sided and two-sided cooling by means of liquid impact jet.

3. Directly cooling the main plate or DBC substrate using concepts such as Danfoss ' shower design power " using a jet impact or flow of fluid through windings channels.

4. Directly bilateral cooling of back- to -back modules with and without ribs integrated with DBC substrates.

5. Microchannel coolers built into main plates either integrated with DBC substrate or in a special personalized packaging design.

6. Arranged power modules and liquid cold plates using extruded channels, folded fins and microchannels cold plates.

In many applications where liquid filtration is not desired, flowmeters channel they must be with enough big size (~2-3 mm) to avoid blockage by particles and sediment in the cooling system liquid. The high fluid velocities and turbulator inserts are usually used to improve the heat transfer coefficient in such big channels, including in liquid cold plates type pipe. This type of approach provides limited possibilities for improving the heat transfer area. Alternative approach developed recently [19], uses helicoidal flow paths to create a strong secondary high - swirl flow to achieve high heat transfer coefficients of the flow channel wall and parallel flow paths to reduce the fluid velocity and the corresponding pressure gradient. The increase in area is achieved by orienting the spiral trajectory so that its axis is normal relative to the base. This design a concept called " vortex " liquid cold plate " or VLCP, is shown in figure 8 in the double - sided version cooling. This option is ideal for cooling IGBT modules, thyristors or diodes sequentially, as shown in Fig. 9.

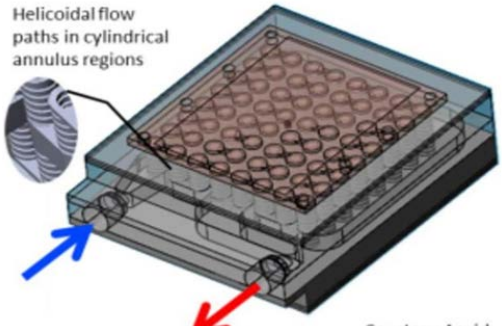

Fig. 8. Vortex Liquid Cold Plate in double - sided version cooling

In the example considered for performance illustration, an IGBT dissipating 1600 W is attached on each side of a VLCP with thermal interface grease. The size of the main IGBT plate is 140 x 190 mm and is accepted uniform thermal flow on the contact IGBT zone. Cooling is provided by a water-glycol cooling liquid with 50% glycol by volume, flowing at 11 litters per minute (LPM) at a temperature of 80ºC at the cold inlet plate. In these conditions the maximum surface temperature of the cold plate is 91.5ºC, which leads to thermal resistance of Rsf = 3.6ºC/kW - efficiency is 47%. For comparison, thermal resistances of the appropriate type of pipe and displaced folded fins type liquid cold plates for the same application conditions are 19ºC/kW and 5.6ºC/kW respectively. The pressure drop of the VLCP was 52 kPa versus 10 kPa for the type of pipe and displaced structures with folded fins.

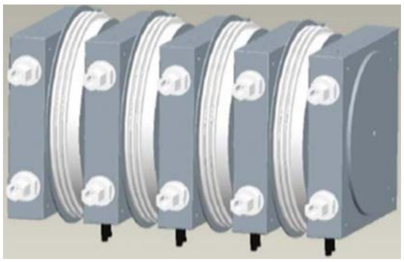

Fig. 9. Diodes connected in series cooled using Vortex Liquid Cold Plates

III. CONCLUSION

Significant progress has been made in air cooling technology power electronic converters. The massive copper plates and heat pipes embedded in the foundations, significantly improve heat distribution in air - cooled radiators cooling. Significantly high energy efficiency is achieved when using contour cooling thermosyphons for more efficient heat transfer throughout main area in contact with the power supply module and passive heat transport in air Cooling. The new concepts for liquid cooling are being considered. cold plates that are suitable for one-sided semiconductor cooling utensils, as well as for double-sided cooling of stacked. Efficiency estimates are provided through application examples.

Although the reliability of some technology is in the process of development and proofing cooling technology has a serious impact on reliability, energy efficiency, dimensions and price of power electronic converters.

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