# Heat Management in Power Converters: From State of the Art to Future Ultrahigh Efficiency Systems

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*Abstract*—**Thermal management is a key design aspect of power converters since it determines their reliability as well as their final performance and power density. Cooling technologies have been a research area in electronics since the 1940s and, in the last 15 years, the number of articles related to this field has grown significantly. At present, thermal management is essential in new disciplines and it is a critical enabling technology in the development of power electronic systems. This paper aims at presenting a review of the state-of-the-art technology and provides future design guidelines for high efficiency power electronic converters. The main design trends are focused on the need to develop cooling systems able to manage high local density heat fluxes due to two converging trends: higher power dissipation and smaller module size. Considering the latest advances in thermal management, as well as the huge improvement in power electronics in the last decades, a review and classification of the main thermal management techniques is presented. Besides, they are compared considering important parameters such as peak power dissipation, efficiency, cost/complexity, power density or technical maturity, and a design example for an ultrahigh efficiency converter is presented.**

*Index Terms*—**Cooling technologies, high efficiency power electronic converters, home appliances, induction heating, thermal management.**

## I. INTRODUCTION

TEMPERATURE is the main cause of malfunction and eventually failure in electronics [1]–[4] and, consequently, reliability in power electronic systems is strongly dependent on it: the higher the temperature of a semiconductor, the worse is its reliability and durability. It severely limits mean life time of electrolytic capacitors and batteries, but also affects directly to semiconductors and can cause system failure due to thermal stress [2], being especially critical in power modules. For these reasons, it is essential to provide proper thermal management in power electronic systems.

The junction temperature must be kept below its maximum rated value given by the manufacturer, typically between 125 and 175 °C for Silicon power devices. The thermal circuit of Fig. 1 is commonly used to estimate the junction temperature in steady state, which is the worst-case condition, where $T_J$ and $T_c$ denote the temperature in the junction and case, respectively, and $P$ is the power loss. In this approach, equivalent thermal resistances are used to model the behavior of each element. The junction-to-case thermal resistance ($R_{\theta JC}$) is specified by the manufacturer and cannot be modified. However, resistances from the case to the ambient represent the effect of the different cooling technologies used to evacuate the heat from the semiconductor, and the power electronic designer has to choose wisely among the wide spectrum of available solutions.

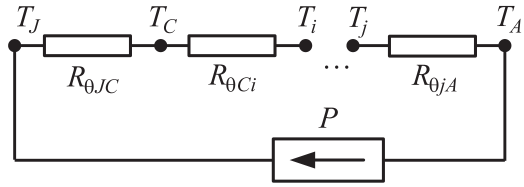

Fig. 1. Thermal circuit.

Cooling technologies have been an area of research in electronics since the 1940s [5], when the effort was intended to find the best method to cool vacuum tubes. In recent years, this effort has grown significantly trying to manage higher density heat fluxes, predicted by thermal roadmaps issued from different technical agencies when studying projection trends in energy dissipation [6]–[8]. These projections have usually followed the well-known Moore's law, which has been used repeatedly to try to guess the evolution of thermal needs [9]. Thermal management has overcome the limits imposed by the ever-increasing demands of applications, introducing new advanced cooling technologies.

Twenty years ago, Lasance [10] pointed out several main factors to explain the importance and influence of thermal management in the operation of electronic systems. Among these factors, one remains true at present: Inside the industrial environment, thermal design uses to be an afterthought matter only if problems arise. Strategies to solve the problem tend to use previously adopted reliable solutions. Proposed solutions are often oversized to avoid unexpected failures and, in general, they have not raised any general approach to optimize the cost and the efficiency. Little effort is devoted to find optimal solutions from the point of view of system performance, however thermal planning can help the system to save money and to work more efficiently.

Most of the thermal management systems are constrained by two requirements: high power dissipation, necessary to achieve better benefits, and smaller module size, due to miniaturization.

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Manuscript received July 06, 2015; revised October 30, 2015; accepted December 22, 2015. Date of publication December 30, 2015; date of current version June 24, 2016. This work was supported in part by the Spanish MINECO under Project TEC2013-42937-R, Project CSD2009-00046, and Project RTC-2014-1847-6, by the DGA-FSE, by the University of Zaragoza under Project JIUZ-2014-TEC-08, and by the BSH Home Appliances Group. Recommended for publication by Associate Editor M. Liserre.

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Digital Object Identifier 10.1109/TPEL.2015.2513433

TABLE I
CLASSIFICATION OF COOLING TECHNOLOGIES

| Coolant agent →<br>Transfer mechanism ↓ | **Solid** | **Gas (air)** | **Liquid** | **Two- phases** |
|---|---|---|---|---|
| **Conduction** | Conduction plates and Heat sinks (a.1) [24]<br>Thermal Interface Materials (a.1) [25-27]<br>Advanced conduction plates (a.1) [24] | | | |
| **Natural convection** | | Air cooling (b.1) [41-42] | Immersion (c.4) ) [66,85-86] | Immersion (c.4) [66,85-86] |
| **Forced convection** | | Standard fans (b.2) [41-44]<br>Piezoelectric devices (b.3) [45-49]<br>Synthetic Jet impingement (b.4) [50-51]<br>Electrohydrodinamics (b.5) [52-59]<br>Thermoacoustic (b.6) [60-62] | Cold plates (c.1) [22-23]<br>Microchannel (c.2) [68-79]<br>Electrowetting (c.3) [80-84]<br>Immersion (c.4) [66,85-86]<br>Jet impingement (c.5) [68], [87] | Cold plates (c.1) [22-23]<br>Microchannel (c.2) [68-79]<br>Electrowetting (c.3) [80-84]<br>Immersion (c.4) [66,85-86]<br>Jet impingement (c.5) [68], [87]<br>Heat pipes (d.1) [90-93]<br>Spray (d.2) [94-95]<br>Phase change material (d.3) [96-98] |
| **Magnetocaloric effect** | Magnetic cooling (a.2) [28-30] | | | |
| **Peltier effect**<br>**Tunnel and Thermionic effects** | Thermoelectric cooling (a.3) [31-34]<br>Thermotunnelling and Thermionic cooling (a.4) [35-40] | | | |

This combination may lead to dangerous local heat densities and technologies have focused mainly on the need to remove the quantities of increasingly larger heat, resulting in expensive and bulky systems. Moreover, energy cost of these bulky solutions cannot be neglected leading to a decrease in the overall system performance.

Besides, the development of new power devices, such as wide bandgap devices (WBG), as well as high performance converter topologies has led to new implementations requiring new and innovative cooling techniques to achieve an efficient implementation (power dissipation density for silicon devices is close to 100 W/cm$^2$ while WBG devices can reach up to levels of kW/cm$^2$, so specific techniques as microchannel liquid cooling and on-chip thermoelectric coolers must be used to meet this challenge [11]). Moreover, modern electrical machines also require high performance thermal management solutions [12]–[14]. Considering the importance of this topic, this paper aims at reviewing the main cooling techniques available and their main features, enabling a proper thermal management selection.

The remainder of this paper is organized as follows. First, a review of the state-of-the-art of cooling technologies is described in Section II. Section III discusses the reviewed thermal management solutions on the basis of a parametrical analysis. After that, a design example using the proposed technology is presented in Section IV. Finally, the main conclusion of this paper is drawn in Section V.

## II. STATE OF THE ART

As stated in [15], the whole cooling system must cover three main targets to fulfill the final purpose: heat removal from devices, heat transport through the module, and heat convection out of the module.

These objectives can be mapped to the thermal model of Fig. 1, in which each layer corresponds to a cooling technology. Depending on the adopted solution, the number of layers, i.e., cooling technologies, from case to ambient may vary.

Different criteria to classify the cooling technologies can be found along the literature. In [16], Scott classifies cooling techniques using heat flux density units (W/m$^2$) to measure their heat transfer effectiveness. In [17], Lasance considers the difference of temperature using heat transfer coefficient (W/m$^2$·K). Generally, most of references focus on those techniques able to manage and eliminate high heat fluxes related to power electronic or microelectronic stages [15], [18]–[23]. In this paper, the proposed classification has been made according to the heat transfer mode and the coolant agent used by each technology, leading to an intuitive and easy-to-use classification, as shown in Table I. It is important to note that although currently most of the thermal management solutions rely on conduction and convection transfer modes, radiation is also present as an auxiliary transfer mechanism in most of them. The next lines describe the main operation principles and features of each cooling technique following the proposed classification.

### *A. Solid-State Cooling Technologies*

Solid-state technologies comprise several technologies that have in common the use of solid devices either using conventional heat conduction or thermoelectric effects. This section reviews the main techniques from the commonly used heat sinks to emerging magnetic and thermoelectric/ionic devices.

*1) Heat Sinks, Thermal Interface Materials (TIM), and Conduction Plates:* Heatsinks, conduction plates, and TIM) are one of the most common thermal management techniques which are based on the conduction heat transfer mechanism.

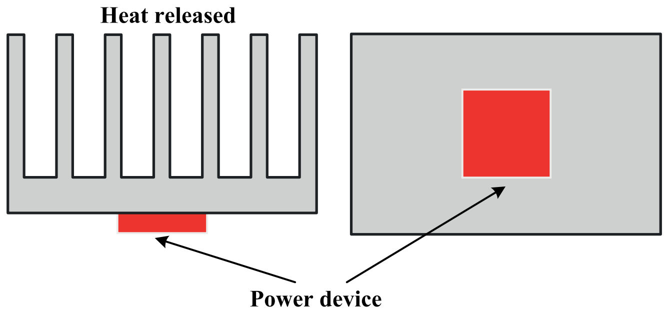


Fig. 2. Heat spreader and heatsink.

Plates and heat sinks made from aluminum are the cheapest passive conduction methods, but these solutions present limited performance in terms of power dissipation and power density, and are used in not very demanding thermal applications. The thermal conductivity of aluminum is about 200 W/m·K and the maximum heat flux able to be dissipated depends on geometry [24] but is usually less than W/cm$^2$.

Heat spreaders are used to maximize the contact surface area between the case of semiconductor and the cooling medium surrounding it (see Fig. 2) to improve heat transference from the basic natural air cooling.

The thermal contact resistance between the case and the heat spreader depends on several factors, for example, contact area or surface flatness. To increase thermal transfer efficiency, TIMs are used to fill the gaps and eliminate the air between the packaging and heat sink. At present, TIM is a cutting-edge technology. Excellent reviews can be seen in [25]–[27].

For high performance systems, advanced conduction plates are advanced heat spreaders used in applications where a highly efficient transfer of heat is needed, such as satellites and military aircrafts. Research in this field focuses on finding new lightweight and high conductivity materials, such as pyrolytic graphite [24]. Thermal conductivities of advanced solutions can be as high as 1700 W/m·K, but restricted to 2-D heat spread, requiring consequently thin plates. Heat fluxes of tens of W/cm$^2$ can be reached and thermal diffusivity of pyrolytic graphite reaches 1220 mm$^2$/s much higher than the aluminum (84 mm$^2$/s) which contributes to a better heat transfer.

*2) Magnetic Cooling:* Magnetic cooling is based on applying variable magnetic fields on magnetocaloric materials, leading to a change in the temperature. Fig. 3 shows magnetic cooling cycle used in this technology. Although its current applications are usually focused on to refrigerator appliances, air conditioning, or heat pumps, continuous research in this field suggests future applications related to other areas [28], [29].

This emerging technology may have interest in those applications with volume and weight constraints, and where high efficiency is a must. Besides, it has been discovered recently that straining and relaxing some materials can produce similar results to magnetocaloric effect. This opens a way to apply nanotechnology for cooling electronic chips [30].

*3) Thermoelectric Cooling:* This technique is based on the Peltier effect [31] and its implementation is referred also as solid-state heat pumps. A dc current flowing through the module produces heat transference so that each side of the module is cooled or heated, respectively (see Fig. 4).

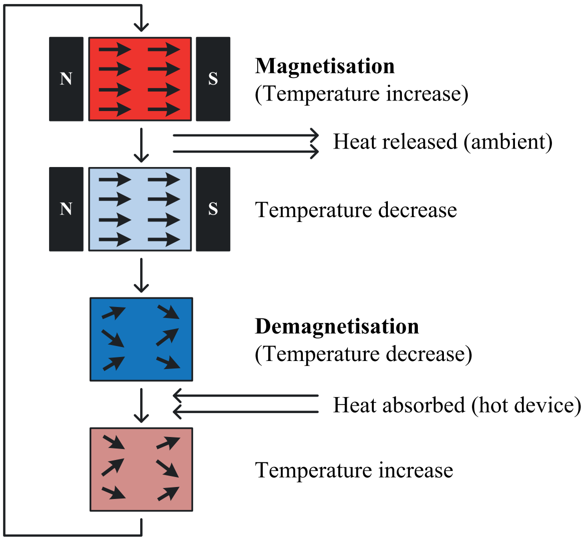


Fig. 3. Magnetic cooling principle.

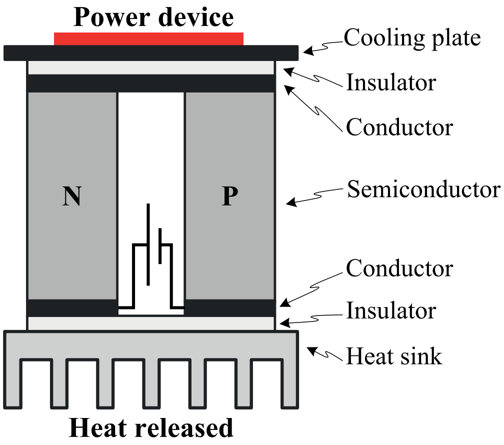


Fig. 4. Thermoelectric cooler.

The main advantages of this technique are its higher reliability, precise temperature control (which allows a better transient response when temperature changes), reduced weight, and volume. However, the maximum power dissipation is limited to several tens of watts (reaching heat fluxes of W/cm$^2$), the cost is higher than other conventional techniques, and the efficiency (according to the definition of Section III) is very low ($<10$), which are serious handicaps in some applications [32]–[34].

*4) Thermotunneling and Thermionic Cooling:* This technique is derived from thermoelectric cooling and aims to increase the efficiency of the system by addressing the nanoscale phenomena, i.e., tunnel or thermionic effects [35]–[37]. This approach uses new materials or structures such as synthetic diamond, graphene, carbon nanotubes, superlattice, and/or heterostructures to improve the efficiency [38], [39]. This technique has a great potential and significant research efforts are currently being paid to prove the possibility of applying the well-known thermoelectric effect with increased efficiencies [40].

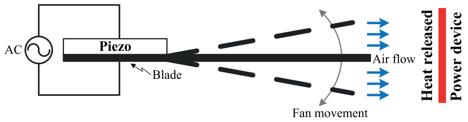


Fig. 5. Piezoelectric fan.

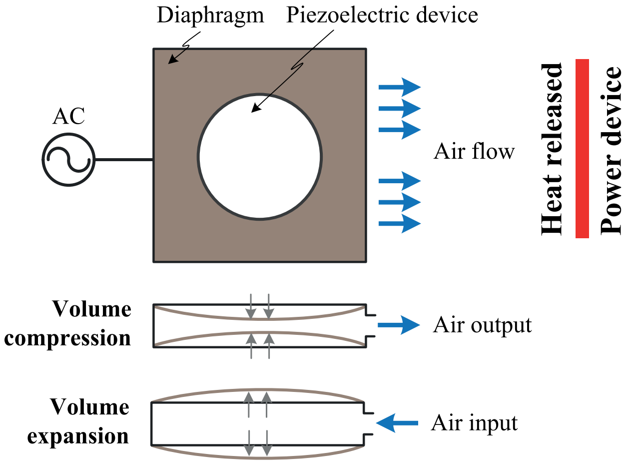


Fig. 6. DCJ.

### *B. Air Cooling Technologies*

Air cooling techniques take advantage of a gas fluid to increase heat transfer exchange without the complexity of liquid systems. This section reviews the main natural and forced convection techniques and their implementation.

*1) Air Cooling (Natural Air Convection):* The simplest form of cooling technology uses natural air convection to dissipate heat from the case of the semiconductor. It occurs due to the variation of density produced by temperature differences between the surface to be cooled and the fluid surrounding it. Following the system in Fig. 1, there is only a thermal resistance from case to ambient. This method is the cheapest one but it is only used when the heat to be drained is very low, typically a few watts (heat fluxes less than W/cm$^2$) [41], [42].

*2) Fans:* In order to lower the thermal resistance between the heat sink and the ambient, forced convection is usually applied. The use of fans in combination with heat sinks is a straightforward implementation commonly used in most power converters. Typical values of forced-convection heat transfer coefficient are in the range 25–250 W/m$^2$·K [41], [42]. Heat fluxes near tens of W/cm$^2$ can be obtained and considering typical values of heat dissipated (tens to hundred watts) and fan power consumption (watts), the efficiency varies from 10 to 100. The main limitation of such systems is the high volume/weight ratio and, consequently, poor power density achieved [43]. A discussion about air cooling limits in heat sink plus fan systems can be found in [44].

*3) Piezoelectric Devices:* Piezoelectric devices are used in forced convection in order to generate air flow [45]. There are three different types of devices that use the well-known piezoelectric effect applied to cooling electronics: piezoelectric fans, dual-piezoelectric cooling jets (DCJ), and piezoelectric microblowers.

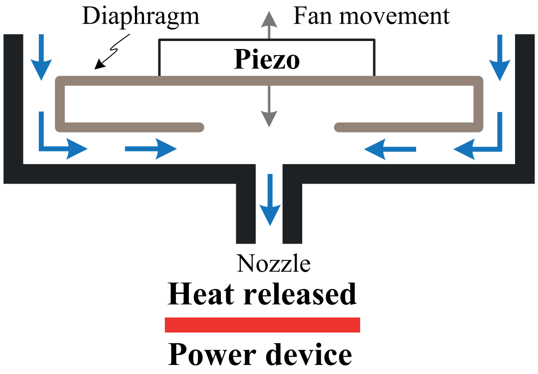


Fig. 7. Piezoelectric microblower.

Piezoelectric fans (see Fig. 5) use a cantilever operating in resonant mode with the electrical input to amplify the motion of the transducer. DCJs (see Fig. 6) are formed by two metal plates which are bent simultaneously when the piezoelectric transducer is working in resonance. Finally, microblowers (see Fig. 7) are similar to DCJs, but they are based on a vibrating diaphragm which makes the air flow enter the device and expels it through a hole located in the center.

All of these piezoelectric devices are intended to be used when the heat to be dissipated is not more than a few tens of watts (heat fluxes about W/cm$^2$) but they share interesting advantages as very low power consumption (hundreds of milliwatts) which delivers efficiencies as high as 300 or 400, and good characteristics related to noise, reliability, and performance [46]–[49].

*4) Synthetic Jet Impingement:* As it occurs with piezoelectric microblowers, synthetic jets use turbulent air flow to improve the heat transfer efficiency. An electrically or magnetically controlled diaphragm is also utilized to pump the air [50]. They can also be classified as small form factor cooling technologies able to manage tens of watts (similar parameters as piezoelectric devices). Its main advantages are its high reliability due to the absence of mobile mechanical parts, low noise, and low power consumption. Currently, technology research in this field is focused on developing even smaller solutions [51].

*5) Electrohydrodynamics (EHD):* Classical air cooling methods are based on the conversion of mechanical energy to fluid energy through the use of any kind of fan. However, EHD techniques rely on the electric to fluid (kinetic) energy conversion and are based on the well-known corona effect (see Fig. 8). Although EHD principles have been known for years, only recent efforts have shown its ability to be considered a feasible cooling technology [52]. The main advantages of EHD are its silent operation, absence of vibrations and mobile parts, little power consumption, flexible form factor, and ability to be scaled to smaller dimensions. However, its main disadvantages are the high operating voltage and the degradation of the electrodes producing the corona effect. Nowadays, this is a very active research field with several trademarks and patents: *Silent Air Cooling Technology* used in laptops [53], [54], *Ionic Cooling Engine* for cooling LEDs in lighting applications [55], [56], or

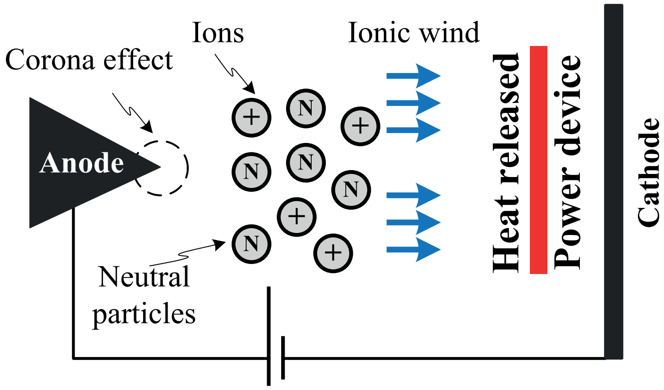


Fig. 8. EHD cooling.

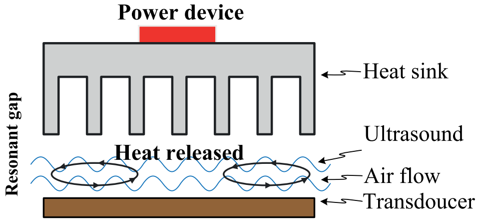


Fig. 9. Thermoacoustic cooling.

*Ionic Wind Generator* also used in computers [57]. In all cases, the power dissipation is around tens of watts (heat fluxes about W/cm$^2$) with efficiencies less than 100.

An interesting approach was introduced in [58]. The research focus is on the use of EHD at nanoscale. At this level, the applied voltage to produce corona effect can be reduced significantly, and it may enable a new generation of self-cooling chips with no need for external cooling.

In [59], Wang *et al.* made a comparison between standard fans, piezoelectric fans, synthetic jets, and EHD on the basis of a similar heat dissipation of 50 W. Conclusions show that piezoelectric devices offer the highest efficiency but lower heat transfer capability than competitors, and EHD and piezoelectric devices achieve the lowest volume.

*6) Thermoacoustic:* Thermoacoustic coolers are based on sound capability to pump heat called thermoacoustic effect. To achieve this, high-amplitude sound waves are generated in a resonator to produce pressure changes (see Fig. 9). Consequently, sound intensity controls the temperature difference achievable [60]. The application of thermoacoustic coolers in cooling electronics presents several advantages such as silent operation, no moving parts, and reliability/simplicity, but if lacks of enough power dissipation capability, i.e., a few watts (heat fluxes less than W/cm2), and efficiency needs to be improved (values less than 10) [61], [62].

### C. Liquid Cooling Technologies

When thermal management has to deal with higher power densities, liquid cooling is preferred over air or solid cooling [63]–[65]. Liquids have higher thermal conductivity and higher heat density than other coolant agents. Acoustic noise coming from fans and extra weight, volume, and cost due to heat sinks are disadvantages for air cooling. However, leakage, corrosion, flammability, toxicity, electrical conductivity, and condensation must be taken into account to prevent future problems in the cooling system. Liquid coolants can be divided (according to their conductivity) in three groups: direct immersion of hot device is possible, direct immersion is not possible but a leak will not damage the electronics, and direct immersion is not possible and leakage will damage the system. An excellent review of properties and cautions of liquid coolants can be found in [66].

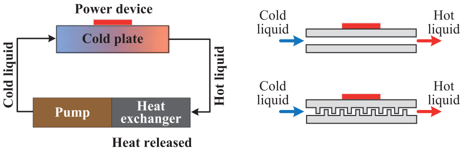


Fig. 10. Cold plate and microchannel.

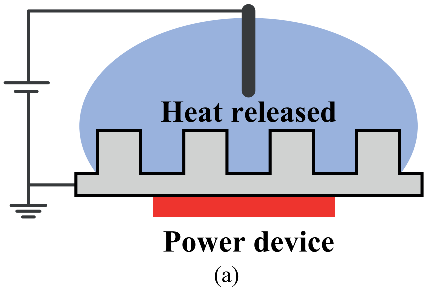
Good reviews for liquid cooling applied to high-heat fluxes can be found in [23], [67], and [68]. Traditional classification of liquid cooling technologies is performed depending on whether the liquid is in contact with the device to be cooled or not, i.e., direct (electrowetting, jet impingement, immersion) and indirect methods (cold plates).

*1) Cold Plates:* Cold plates perform a similar function to air-cooled heat sinks, using liquid as coolant agent and taking advantage of the higher heat transfer properties of liquids. However, it is important to note that liquid cooled systems based in cold plates also need a heat exchanger to release to the ambient the heat and a pump to move the liquid through the system (see Fig. 10). Many efforts have been done in cold plate design to increase the surface in contact to liquid, improving heat transfer (heat fluxes about tens of W/cm$^2$ and efficiencies between 300 and 500) [22], [23]. From this trend, microchannel technology appeared and, at present, it can be considered as an independent technology.

*2) Microchannel:* This term is used when the hydraulic diameter of the designed heat sink is about ten to several hundred of micrometers (see Fig. 10). By using this technology, heat flux near 1000 W/cm$^2$ can be achieved and research results aim at increasing this value. Expected values of efficiencies can be higher than 1000. Coolants used vary from simple deionized water to any kind of refrigerant or more recently nanofluids and the flow rates oscillate from tens to hundreds of mL/min [68]–[73]. As a first approach, smaller channels produce higher heat transfers but also produce higher pressure drops. This fact has forced the research in pump and micropump technology able to overcome this limitation [74]–[77].

Another aspect that is being investigated in this technology is the replacement of water as coolant agent for liquid metal, which is sometimes referred as liquid metal cooling. Experiments with this technology show promising results beyond 1000 W/cm$^2$ using eutectic alloys of different materials as gallium, indium, tin which have the properties of being nontoxic, nonflammable although must be in closed system to prevent oxidation [78], [79].

*3) Electrowetting:* Electrowetting is based on applying an electric field to a fluid to change the surface tension forces



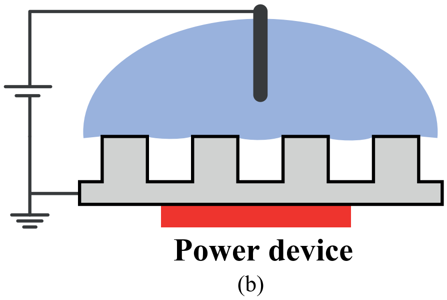


Fig. 11. Electrowetting principles: (a) Electric field applied (wetted surface), (b) Electric field not applied (dry surface).

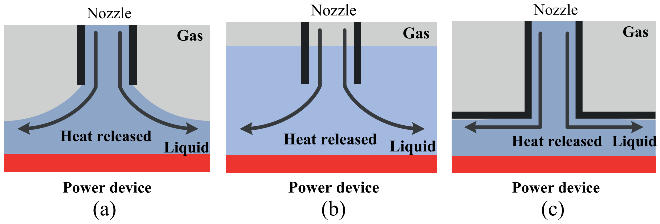


Fig. 12. Jet Impingement implementations: (a) Free-surface jet, (b) submerged jet, and (c) submerged confined jet.

causing a droplet of liquid (volume on the order of $\mu$L) to wet the surface to be cooled (see Fig. 11).

This effect can be seen as a micropump able to move the fluid through a given channel having the advantage of a better flux control and obtaining heat fluxes capabilities about tens of W/cm$^2$ with very low pump power consumption (about milliwatts) which gives very high efficiencies (several thousands). Liquids used in electrowetting are usually deionized water, liquid electrolytes (NaCl, KCl, $K_2SO_4$ . . . ) or mixtures of glycerol, ethanol or ethylene glycol. Ethanol or ethylene glycol can present any toxicity but should not be a problem because they are used in closed circuit [80]–[84].

*4) Immersion:* In this case, the device to be cooled is submerged in the liquid. Depending on the dominant heat transfer mechanism, it may be classified as natural or forced convection, if any kind of pump is used, or may be included in the two-phase cooling technologies if the coolant reaches its boiling point. Currently, its main applications are oriented to microelectronics, but they can be extended to high efficiency and power density power converters. Power dissipations of hundreds of watts have been reported (heat fluxes ranging between 500 and 1000 W/cm$^2$). Pump power estimation using pressure drop and flow rates (8 L/min) show efficiencies about 500. Coolant considerations must be analyzed to obtain a good performance but any dielectric coolant should be used. Reviews report coolant volume estimation about 100 cm$^3$/kW in high power applications [66], [85], [86].

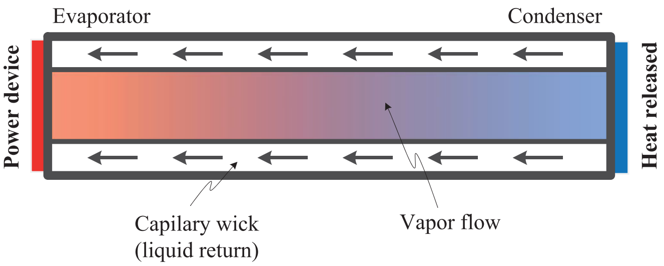


Fig. 13. Heat pipe.

*5) Jet Impingement:* With this technique, the device to be cooled is hit by a high-speed liquid stream, usually created in a great number of holes arranged in matrix at a flow rates of hundreds of mL/min. Jet impingement can be classified in submerged, when the jet flows within the same fluid in the same state and free surface, when the liquid flows into air environment (see Fig. 12). Although performance of jet impingement depends on a large amount of parameters such as the jet velocity and diameter, impact angle, nozzle spacing or fluid properties, higher heat flux (higher than 1000 W/cm$^2$) when compared to other liquid cooling methods is achieved [68], [87]. Very high values of efficiency can be found (near 1000).

### *D. Two-Phase Cooling Technologies*

The liquid cooling technologies reviewed can also be used forcing the fluid to have a change of physical phase instead of remaining as single-phase fluid. Two-phase cooling achieves significant advantages when compared to single-phase cooling: higher heat transfer rates and efficiency, lower flow rates and pumping power, isothermal characteristics, lower size and weight, and lower cost. The main disadvantage is the higher complexity of a two-phase system and the use of toxic fluids, although fluids as R134a are showing interesting advantages when used in two-phase systems (environmentally safe, dielectric and heat transference properties) [88], [89]. This technique can be applied to most of the previously reviewed thermal management techniques and, in the following lines, some of the main current implementations and research trends are reviewed.

*1) Heat Pipes:* Heat pipes can be described as passive two-phase heat transfer devices. This technology has been known for more than 50 years and has been continuously developed since then leading to modern high performance implementations.

Heat pipes consist of three main parts: container, fluid, and wicked structure (see Fig. 13). A source of heat forces the fluid to boil, absorbing the latent heat of vaporization.

The created steam moves towards a colder point, where it is condensed and transfer the heat to the environment through a heat exchanger. The liquid fluid returns to the hottest area driven by capillarity forces generated inside the wicked structure.

Flexibility and high conductivity are the main advantages of heat pipes, allowing heat fluxes ranging between tens and hundreds of W/cm$^2$ involving flow rates of liquid (water or

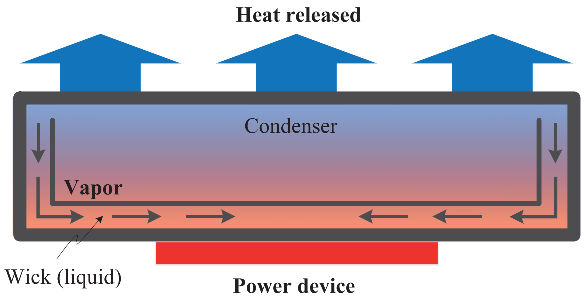


Fig. 14. Vapor chamber.

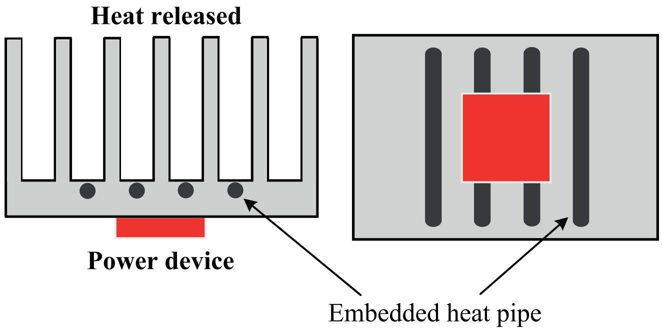


Fig. 15. High conductivity plate.

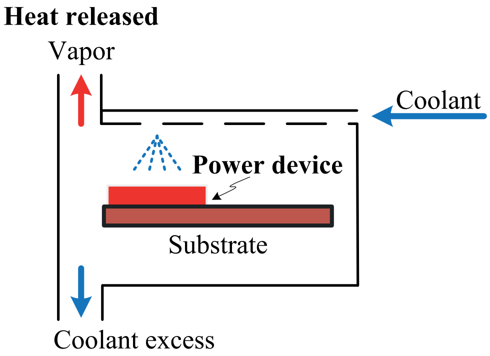


Fig. 16. Spray cooling.

alcohol typically) of about liters or tens of liters/min. However, the main disadvantages are related to temperature limitations and vertical height to be overcome.

There are several special types of heat pipes implementations which are worth to be mentioned due to their relevance. Thermosyphons are a special type of heat pipe in which the fluid is driven only by gravity forces. Vapor chambers are planar heat pipes able to two-dimensional heat spreading with very small gradient temperature and with the capability to dissipate several hundred of W/cm$^2$ (see Fig. 14). Besides, heat pipes can also be found as microscale heat pipes using in this case some kind of liquid metal [90], and embedded in high conductivity plates to increase heat spread and transfer capabilities of simple conduction plates (see Fig. 15). Performance limits of heat pipes and vapor chambers is currently a matter of research [91], [92].

*2) Spray:* Spray takes advantage of vaporization heat to provide high heat fluxes.

According to the method used to produce the spray (see Fig. 16), two types can be found: pressure spray, where a high pressure is applied to a liquid flow through a nozzle, and atomized spray, where a high-pressure air flow stream breaks the liquid into droplets. Although spray can be used in single-phase convection mode, it usually benefits from the fact that the fluid, in contact to the heated surface, starts boiling and extracts the latent heat of evaporation of the fluid. Besides, direct spray eliminates the thermal resistance of heat spreader which contributes to the removal of high heat fluxes and also reduces the power consumption of the pumps needed to move the fluid. One of the main challenges when designing this technique is the selection of a proper liquid with adequate non-conduction thermal and chemical properties to allow direct contact to the hot device to be cooled, and avoiding the creation of undesired liquid layers which may degrade cooling efficiency [1]. Spray cooling is a complex technology which depends on many physical and geometric parameters. Flow rates of liters or tens of liters per hour have been reported to manage heat fluxes of tens to hundreds of W/cm$^2$ with high values (300–500) of efficiency, and much effort has been and is being done to optimize them [93], [94].

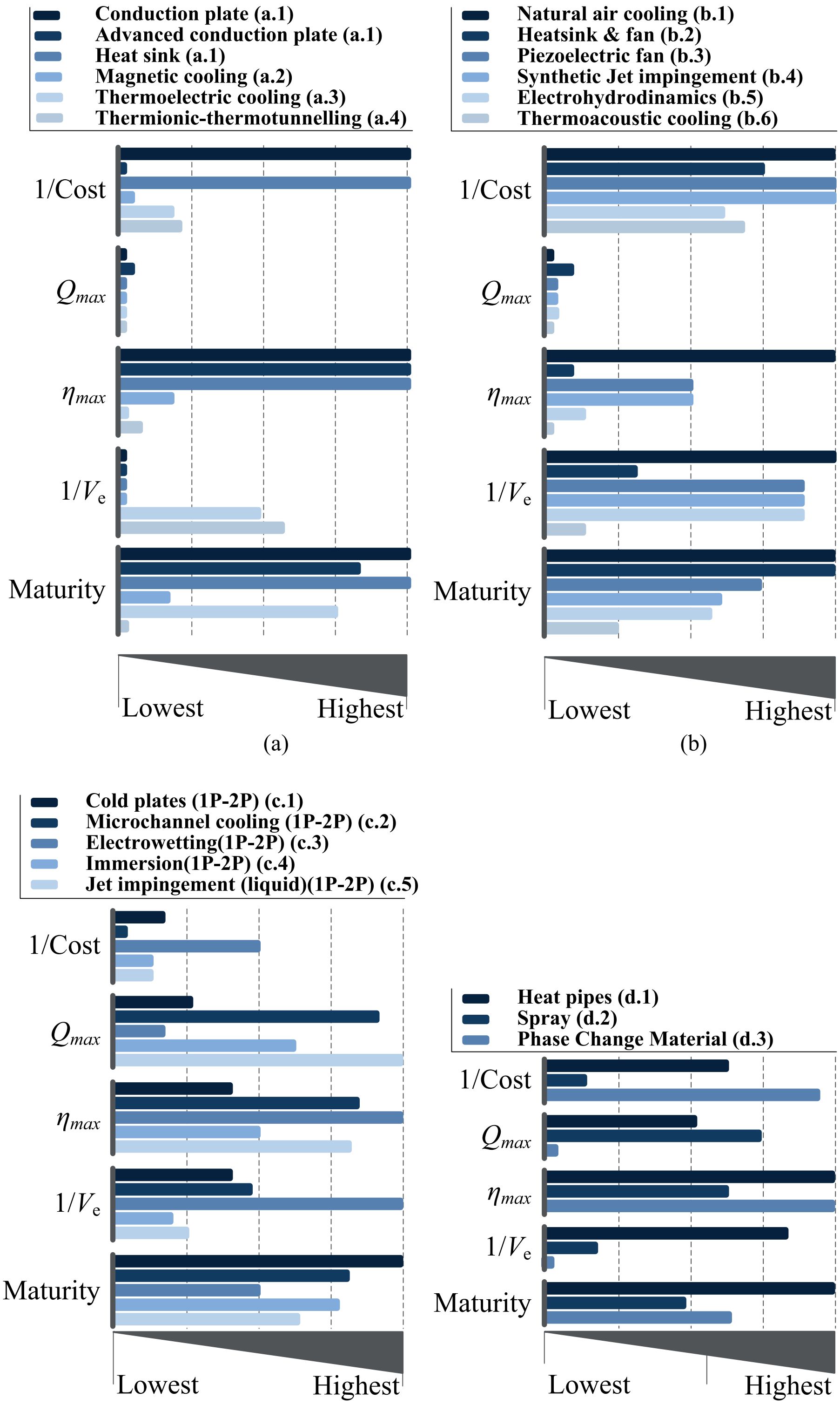
*3) Phase Change Materials (PCM):* Finally, phase change materials (PCM) cooling technology exploits the physical property of the materials by which they are able to release heat at constant temperature during a phase change. It is mainly oriented to applications involving transient or cyclic power dissipation [95]. It can be seen as a passive method used to reduce the size and space in the heat sink and, consequently, reducing costs. Since one of the main drawbacks is its high thermal resistance, it is usually combined with heat spreaders and active temperature control systems, allowing the global system to increase its efficiency by decreasing the energy consumed [96]. Heat fluxes are similar to the obtained ones using heat sinks. Considerable effort is devoted to study the materials used in PCM [97].

## III. THERMAL MANAGEMENT DISCUSSION AND FUTURE TRENDS

The previous section has reviewed the most important and emerging thermal management techniques with potential application to power converters. When designing a specific application, several figures of merit must be taken into account to select the right one. Some of the most important are summarized in Fig. 17: peak heat dissipation ($Q_{\max}$), electrical efficiency ($\eta_{\max}$), volume ($1/V_e$), cost/complexity, and technical maturity.

The $Q_{\max}$ parameter is given in W/cm$^2$, and numerical values can be found in each section. The efficiency of the cooling system is calculated as the ratio of the heat removed to the power input (also known as coefficient of operation) and should not be confused with the efficiency of power module, calculated as the ratio between the useful energy output and the energy input to the power module. The efficiency of the overall system (power module and cooling system) is lower due to consumption of the cooling system.

When passive methods have been compared, efficiency approaches to infinity (represented as highest value). This should be taken into account in the analysis of bar charts of Fig. 17. The volume parameter should be understood as volume per watt



(a) (b) (c) (d)

Fig. 17. Bar charts comparing the main thermal management techniques reviewed considering the main figures of merit: (a) solid-state techniques, (b) gas techniques, (c) liquid techniques, and (d) two-phase techniques.

dissipated, so $1/V_e$ takes the highest value when a technology is able to dissipate a great amount of heat using a small volume. Finally, Cost/complexity and technical maturity parameters should be understood in a qualitative way.

To homogenize the comparison between technologies, lowest and highest limits in Fig. 17 are common to all the represented technologies. Analysis of parameter $Q_{\max}$ in Fig. 17(a) and (b) shows a qualitative value much lower than the showed in other technologies. Although numerical values about all the technologies can be found in each section, it must be taken into account that advanced conduction plates are able to dissipate as much as three or four times the amount dissipated by the rest of technologies of the group of Fig. 17(a). Similar comments can be done when comparing standard fans used with heat sinks (the highest in its group) and the rest of technologies of Fig. 17(b).

Peak power dissipation has been usually the most important design parameter, in conjunction with cost, especially when high power systems are designed. Considering this aspect, liquid cooling and two-phase techniques (see Section C) achieve the highest power dissipation and should be selected for such systems.

However, additional considerations should be taken into account for modern high efficiency and power density converters. In such systems, both efficiency of the thermal management system and volume play a key role to achieve high global efficiency and power density values. Some techniques achieve high electrical efficiency, such as conduction or air cooling, whereas their specific volume is too high, leading to poor power density values.

In addition to the technical parameters aforementioned, technical maturity is a key parameter, especially when designing mass market devices, since it is directly linked to the final product reliability and performance. Considering this aspect, this paper has reviewed well-established techniques such as conventional heatsinks or liquid cooling to emerging techniques such as magnetic, EHD, and solid state ones. The final decision will depend upon the required performance and risk.

Finally, cost is always a constraint that must be considered in power converter design, including the thermal management system. As it is highlighted in Fig. 17, each implementation leads to a different cost highly linked to its physical dissipation mechanism. The final trade-off between cost and performance will depend on each application.

This chart is designed to provide a quick overview of the available techniques that can be chosen to fulfill one or various parameters and to maximize one or the rest of the other ones. It is important to note that there are other parameters different from the analyzed ones (all of these, limiting factors to design the cooling system) that may be essential in some applications. For example, in liquid cooling systems, there always exists a fluid leakage risk and even a potential danger if the fluid presents any kind of toxicity. Standard fan or, to a lesser extent, piezoelectric fan, may present noise problems that can become annoying and, in some applications, unacceptable. When gravity is used in the cooling system (i.e., thermosyphons), orientation is a very important design parameter. EHD techniques use high voltages than can be potentially dangerous and require proper isolation. Besides, ionized currents could damage semiconductor devices.

Although discussion is focused on static performances, dynamic performance is a critical point when fast transient cooling is required. In general, systems relying on the use of forced convection, especially liquid, or phase change, achieve the highest response time, being recommended for applications with fast thermal transients. However, when it is not possible to use liquid or two-phase cooling, or when these techniques are not recommended (i.e., satellites or military aircrafts), thermal management must rely in most cases on conduction techniques. At this point, diffusivity of materials used in heat sinks and conduction plates varies greatly from conventional ones, as aluminum or copper, (84 and 111 $\text{mm}^2/\text{s}$, respectively) and the new ones, as pyrolytic graphite (1220 $\text{mm}^2/\text{s}$), used in advanced conduction plates used when a better thermal response is required. Finally, TEC coolers shows precise temperature control which allows a better transient response when temperature changes.

Future design trends include both new and innovative techniques, such as some of the reviewed in this paper, and significant advances in classical ones that lead to a breakthrough in thermal management systems. As stated at Section I, the main purpose of cooling technologies is to minimize existing thermal resistance between the case and the environment. However, junction to case resistance is usually given by the manufacturer and thermal technologies do not act on it. Recently, many efforts are being directed to try to change this fact and the so-called on-chip cooling technologies are strongly emerging in this field. Their objective is to cool directly the silicon die, so modifications must be accomplished in the process of fabrication of chips to dissipate directly the heat.

Of the reviewed technologies, the old and well-known concept of heat sink reinvents, replacing great volumes of aluminum by carbon nanotubes directly attached to the surface of silicon chips [38] or by the use of graphene sheets used as heat spreaders [39]. Thermionic cooling uses carbon nanostructures to apply thermoelectric effect more efficiently [35]. The use of EHD at microscale was referenced in [58] obtaining high conductivities and reasonable good heat fluxes and reasonable efficiencies. Electrowetting is also applied at microscale level in [80] and [82] where the concept of microfluidics (fluids used to cool at microscale) is used.

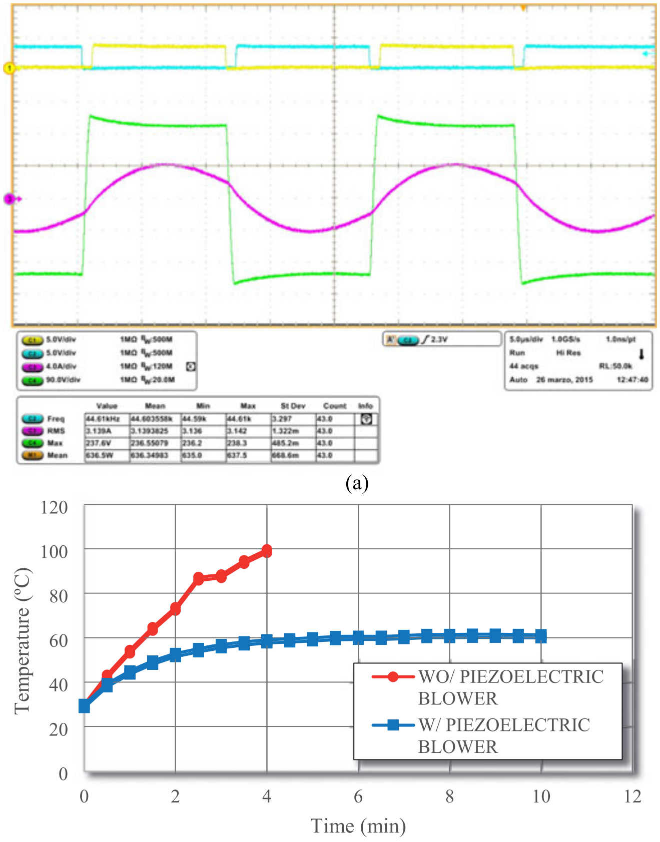
Apart from those references, liquid cooling technologies are developing microscale methods as microjet arrays (jet impingement) [98] and are bringing the microchannel technology to the limit, etching directly an array of microchannels on the silicon [99]. Besides, 3-D cooling techniques will play a key role in modern power electronic systems, especially in high power density converters taking advantage of wide bandgap semiconductors.

Considering modern ultrahigh efficiency and power density designs, the next section details a design example taking advantage of piezoelectric microblowers which enables a high efficiency and power density design with a cost-effective implementation.

## IV. DESIGN EXAMPLE: ULTRAHIGH EFFICIENCY RESONANT CONVERTER

In this section, an ultrahigh efficiency resonant power converter for portable induction heating applications [100], [101] is designed taking advantage of modern thermal management techniques. The converter is a resonant full-bridge inverter designed to supply up to 600 W exceeding 99% efficiency in a 3.5-cm × 5.5-cm PCB.

Fig. 18. Ultrahigh efficiency converter using piezoelectric thermal management: 600 W and 3.5-cm × 5.5-cm PCB.


```
C1 5.0V/div    1MΩ B_W:500M
C2 5.0V/div    1MΩ B_W:500M
C3 4.0A/div    1MΩ B_W:120M
C4 90.0V/div   1MΩ B_W:20.0M

A' C2 ∫ 2.3V

5.0µs/div  1.0GS/s    1.0ns/pt
Run        Hi Res
44 acqs               RL:50.0k
Auto  26 marzo, 2015  12:47:40
```

| | Value | Mean | Min | Max | St Dev | Count | Info |
|---|---|---|---|---|---|---|---|
| C2 Freq | 44.61kHz | 44.603558k | 44.59k | 44.61k | 3.297 | 43.0 | |
| C3 RMS | 3.139A | 3.1393825 | 3.136 | 3.142 | 1.322m | 43.0 | |
| C4 Max | 237.6V | 236.55079 | 236.2 | 238.3 | 485.2m | 43.0 | |
| M1 Mean | 636.5W | 636.34983 | 635.0 | 637.5 | 668.6m | 43.0 | |

(a)

(b)

Fig. 19. Main waveforms (a) and temperature evolution (b) at 630 W.

Thermal management of the proposed converter has been designed considering its output power and efficiency, leading to thermal management needs in the range of watts, as well as its high power density requirements. Considering these aspects and according to the previously discussed review, a prototype featuring an axial piezoelectric microblower has been designed and built (see Fig. 18). The cost of such system represents approximately 15% of the complete system, while enabling improved features.

The full-bridge converter is implemented using 6P385P MOSFET devices from INFINEON placed symmetrically on the PCB. A PCB plane has been designed to enable proper heat transfer and the piezoelectric blower has been placed to direct the air flow over the transistors. By doing so, the convection coefficient is dramatically increased compared with natural convection [102], and a proper thermal design is obtained. It is important to note that this design, suitable only for state-of-the-art high efficiency converters, achieves notably high power density and cooling efficiency.

Fig. 19(a) shows the main waveforms of the proposed converter operating at 630 W, proving its proper operation. Fig. 19(b) compares the device temperature with and without the piezoelectric microblower at 25 °C ambient temperature. As it can be seen, the proposed design achieves a stable thermal design with 35 °C temperature increase, while allowing a high performance and compact design.

## V. CONCLUSION

In this paper, a complete review of the main available thermal management techniques has been developed. These techniques have been reviewed and classified according to the coolant agent and the heat transfer mechanism. As it has been discussed, each one achieves different performance according to figures of merit such as peak power, efficiency, cost, or power density with different levels of technical maturity. The presented review may serve as a guide to select the most appropriate thermal management solution for new and innovative power converter designs, where ultrahigh efficiency and performance is achieved. Finally, this paper is complemented with a design example detailing an ultrahigh efficiency resonant converter design which takes advantage of a piezoelectric microblower to achieve a high power density implementation while maintaining high overall efficiency and low cost.

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