Integral 3-D Thermal, Electrical and Mechanical Design of an Automotive DC/DC Converter

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***Abstract*—Power electronics is finding increasingly more applications in high temperature environments where power density is also a driving factor. The engine compartment of a passenger vehicle is one such example. In this paper, an integral thermal, electrical, and mechanical design of a high power density dc/dc converter operating in the thermally harsh automotive environment is discussed. The interactions and interdependencies between the three design disciplines are considered. It is illustrated how these interactions can be manipulated and used to an advantage in meeting the harsh temperature and high power density requirements of the automotive converter. Packaging and circuit techniques are identified that can be used to this end.**

Two case studies of a 2-kW 14-V/42-V dc/dc converter for application in the automotive environment are considered. The first prototype achieved a power density of 170 W/in^3 while the second prototype, operating with a higher environmental temperature achieved a power density of 120 W/in^3. The experimental structures and practical results are presented. Technology issues concerning the three-dimensional construction of the prototypes that need research attention are also identified.

***Index Terms*—High power density dc/dc converter, three-dimensional (3–D).**

I. Introduction

IN MODERN power electronics, high power density packaging is becoming increasingly important and receiving more attention that ever before. There are many drivers behind this trend with the automotive industry being one of them. In addition to a high power density, the automotive industry also requires that the power electronics implemented within the passenger vehicle must operate in a very harsh thermal and electrical environment. For example, any power electronic system operating within the engine compartment must withstand ambient temperatures reaching 150 °C. The only available form of cooling is the engine liquid coolant that can have a nominal temperature of 85 °C and can be expected to reach 120 °C at 1.4 bar pressure in the near future [1], [2].

With the advent and implementation of the dual voltage 14/42-V system in modern passenger vehicles, it is clear that the amount of power electronics implemented within the vehicles is going to increase [1]–[3]. The dual voltage system can be implemented with many possible architectures each having their own advantages and disadvantages. Fig. 1 shows one possible implementation of the dual voltage system [2], [3]. In all of the proposed architectures, the dc/dc converter between the two voltage levels is common [2], [3]. This converter is required to transfer power between the two voltage levels depending on their power demands. The converter is bidirectional and currently has a typical rating of approximately 2 kW. It is assumed that in the engine compartment the only available means of cooling the converter is the aforementioned engine coolant.

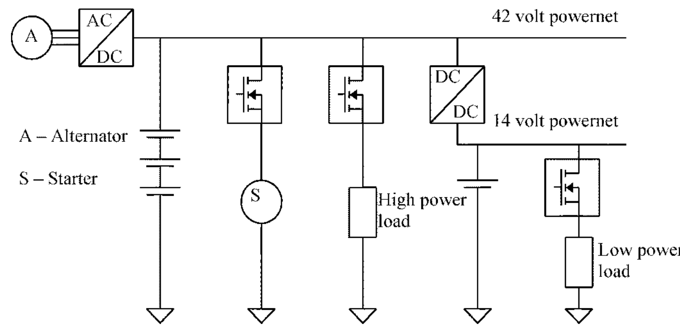

Fig. 1. Possible architecture for the implementation of the dual voltage system.

The implementation and packaging of the dc/dc converter, for use in the engine compartment of a passenger vehicle is the primary focus of this paper. Particular attention is given to the high power density and high operating temperature requirements. The electrical, mechanical and thermal design of the converter must be considered simultaneously due to the high level of interaction between the designs to achieve the desired results.

This paper investigates how to manipulate the three designs so that they complement each other resulting in a design solution meeting the final specifications. In the following section the interactions between the electrical, thermal, and mechanical designs are considered. Once this interaction is understood, electrical, thermal, and mechanical manipulation techniques for achieving the design requirements are considered. Two prototypes using these techniques are presented. Practical results are presented and the two case studies are evaluated and compared to each other. Conclusions are then drawn.

II. Combining the Electrical, Thermal and Mechanical Requirements

The integral electrical, mechanical and thermal design strives to achieve a packaging solution that has the following characteristics:

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1) meets the terminal conversion requirements at full power (electrical design);
2) operates at the desired ambient temperature (thermal design);
3) meets the density or volume requirements (mechanical/spatial design).

To achieve this in three-dimensional (3–D) space, the electrical design (the topology), the thermal design (automotive temperature) and the mechanical design (high power density) must be considered simultaneously for the individual design requirements to be met in a common volume [4], [5]. These three designs are tightly interconnected and any change in one design will have consequences on the others. The relationship between the three designs can be graphically illustrated as in Fig. 2. Each of these three designs has their own set of specifications and each design is connected to the remaining designs with bidirectional arrows. These bidirectional arrows represent the interactions present between the three designs.

The interactions between the three designs can be used to an advantage in trying to meet the temperature and volume specifications. For example the electrical design can be altered to the following.

1) Reduce the stresses in the components by changing the topology. This leads to an increase in the efficiency which relaxes the thermal requirements.
2) Reduce the requirements of large component sizes by changing the topology. This leads to less energy storage requirements and relaxes the density requirements by having a smaller initial volume.

To understand the interactions between the three designs, first consider the requirements of the three design aspects with focus on the operating temperature and high power density requirements of the automotive converter.

A. Electrical Conversion (Topology) Requirements

For a high power density and high operating temperature application, a topology is required that has a relatively low component count and has reduced component stresses. The component stress represent how much heat will be dissipated in the component for a given electromagnetic function. In the case of passive components, the volume and the losses may be traded off. The component stresses are linked to both the thermal and mechanical designs determining the ΔT between the components' hotspot and the environment, and the components volume. The component count is also directly linked to the mechanical design through the components volume.

B. Thermal (Automotive Temperature) Requirements

To operate in the harsh automotive environment, the temperature drop between any material or component and the environment must be made as small as possible. If the ambient or heat sink temperature is high (engine coolants temperature), then a low ΔT will prevent the materials or components from being thermally damaged or destroyed. A small ΔT requires that either the losses in the component or material be low for a given thermal management, implying a low loss density, or the thermal resistance from the component or material to the environment for a given loss density be low. This implies a connection to both the electrical design (low losses) and the mechanical design (low thermal resistance).

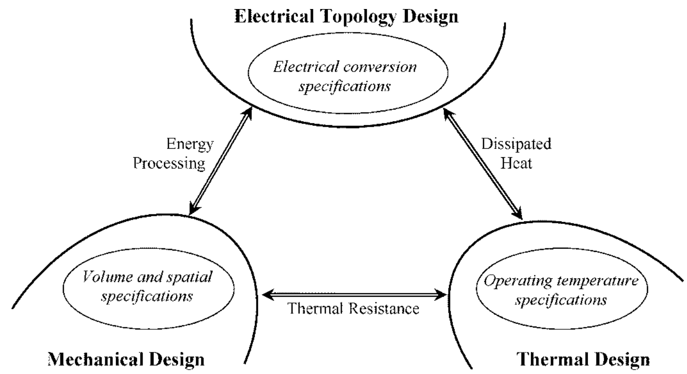


Fig. 2. Relationship between the electrical, thermal, and mechanical designs.

C. Mechanical (Power Density) Requirements

To achieve a high power density, the number of components in the topology should be kept to a minimum and the loss density of the volumetrically expensive components (generally the passive component) must be as high as possible for a given excitation. A high loss density implies a reduction in the volume for a fixed excitation which in turn will result in a higher ΔT between the component and environment. The high power density requirements are linked to the electrical design through the component count and linked to the thermal design through the ΔT between the component and environment.

If the requirements for the dc/dc converter for the passenger vehicle are considered, a contradiction in the high temperature and high power density requirements can be noticed. For a high power density, a high loss density in the volumetrically expensive components is required, but for operating in the thermally harsh automotive environment, a low loss density in the same components is required. This contradiction can be overcome by careful electrical, thermal and mechanical design. For example, the losses in the volumetrically expensive components can be minimized through the electrical design resulting in smaller components. Then together with the appropriate thermal management, a high temperature solution can be found without exceeding the components maximum temperature and still achieving a high power density.

III. 14/42-V Power Converter Modules

In this and the following section, the interactions between the three designs are illustrated with the aid of the high power density dc/dc converter for implementation in the automotive environment. Using the automotive converter, it is illustrated how the design interactions between the electrical, thermal and mechanical designs can be manipulated to produce a final converter structure meeting the operating temperature and volume requirements. The complete design and analysis of the two case studies are not repeated in these sections and can be found in [9]–[12].

A. Operating Environment Constraints

For application in the automotive environment, the engine coolant provides the only available means to transport the dissipated heat away from the power converter. For this reason a thermal interface is defined [4]. This thermal interface is a surface where all of the converters' dissipated heat is conducted to and then exchanged with the environment, in this case the engine coolant. It is assumed that the thermal interface can be treated as an infinite heatsink with the coolants temperature. This is illustrated in Fig. 3 and can be justified by considering the heat that the engine dissipates against that dissipated in the converter. This assumption places significant boundaries on the electrical, thermal and mechanical design of the converter. For example, only thermal conduction can be used in the thermal management of the converter. This is because the vehicles engine compartment is not conducive to thermal radiation, natural or forced air cooling of the converter as the converters location and orientation within the engine compartment are unknown [10]. This means that all the heat dissipated in the components of the converter must be collected and conducted down to the thermal interface with a small temperature drop while achieving a high power density [11].

B. Converter Topology

The topology selected for the automotive converter is the synchronous rectified phase arm shown in Fig. 4. The figure shows the converter topology and the main waveforms. The topology was selected because it has a low component count, supports bidirectional operation and is electrically robust. However, the topology also has its drawbacks. For example, the topology is hard-switching, suffers from mosfet body diode reverse recovery and has high RMS currents in the passive components [6].

The RMS current in the low voltage capacitor, C_{14} in Fig. 4 can be reduce with the appropriate choice in the inductance L [7], [13], [14]. However, it is possible for the RMS current in the high voltage capacitor, C_{42} (parallel combination of bus and decoupling capacitors), to easily be larger than the rated high side current, I_{42} [7]. The high RMS currents in the two capacitors, specifically C_{42} results in a large volume of capacitors being required to prevent component overloading and thermal destruction. This results in a low power density. To increase the power density of the converter, the stresses and the volume of the passive components must be reduced.

The switching losses in the semi-conductors due to the hard switching and reverse recovery issues can be reduced with appropriately selected devices [6].

IV. Integral Electrical, Thermal and Mechanical Design of the Automotive Converter

To achieve a high power density, the converter must have a small volume while not exceeding the maximum operating temperatures of any of the components or materials. There are generally two ways, or a combination thereof, to achieve this. The first is to reduce the component stresses and losses which implies increasing the efficiency, thereby decreasing the volume required to implement the component in. Secondly, the components thermal management or cooling can be increased, decreasing the temperature drop for a given amount of dissipated heat. Both of these approaches are considered in the following section.

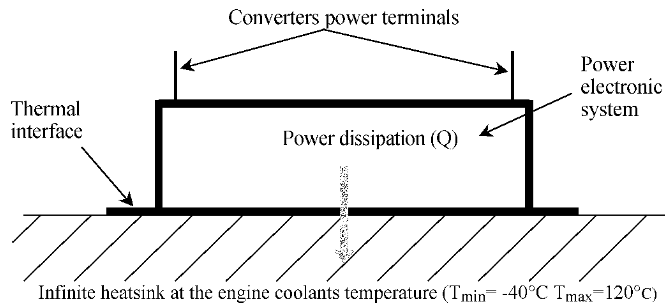


Fig. 3. Packaging and thermal boundary definition.

A. Component Stress Management (Electrical Design)

Through manipulation of the converter topology, it is possible to reduce the component stresses [12]. One such topology manipulation technique is interleaving [7], [8]. Interleaving is achieved by operating more than one phase arm, as illustrated in Fig. 4, in parallel and with all the phase arms sharing common high and low voltage bus capacitors. The phase arms are then operated with a $2\pi/\mathrm{N}$-degree phase shift between the phase switching signals, where N is the number of phases. Interleaving results in an increase in the ripple frequency of the capacitor currents effectively reducing their RMS currents and hence their stress [7], [8].

The resulting RMS current in the inductor and two bus capacitors, $I_{\mathrm{L\_RMS}}$, C_{14} and C_{42}, based on the component waveforms can be fully described as a function of the number of interleaved phases, topology operating parameters and the duty cycle by (1)–(3), respectively [7], [12]. In the equations, V_{42} is the high side voltage, T is the switching period (inverse of the switching frequency), L is the phase inductance, N the number of interleaved phases, D the duty cycle, and n is a modifier which equals $1, 2, 3 \ldots N$ depending on the duty cycle (1)–(3) shown at the bottom of the next page.

By choosing the appropriate number of phases, phase inductance and switching frequency for a given set of operating specifications, the RMS currents in the passive components can be minimized. For a high power density design operating in the automotive environment, reduced RMS currents can lead to reduced component stresses and losses relaxing both the thermal and mechanical design of the components for the given specifications.

The equations also show that the RMS currents in the passive components generally decrease with the increase of the switching frequency. However this does not imply that the switching frequency can be increased without limit. The choice of the switching frequency if not fixed by the given specifications, is limited by the trade-off between the losses in the implemented components and the RMS currents in the components.

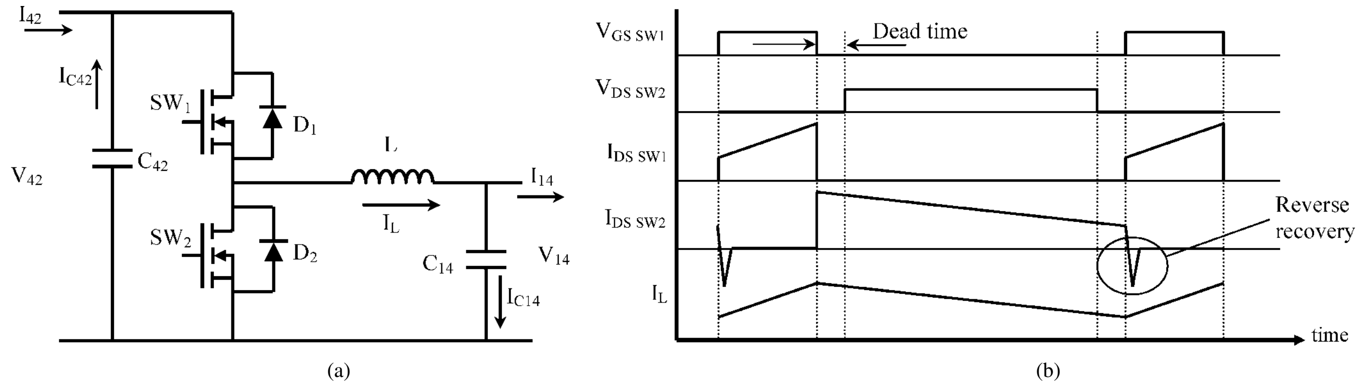


Fig. 4. (a) bidirection synchronous rectified phase arm and (b) switching waveforms.

To illustrate how the RMS currents in the bus capacitors can be manipulated through the number of phases and phase inductance, consider two systems, both 2 kW, one with three phases and the other with four phases, both having the same inductance (4-μ H) and switching frequency (140 kHz).The RMS currents in C_{14} and C_{42} are plotted in Figs. 5 and 6 for a three- and four-phase system as a function of the terminal voltages, V_{14} and V_{42}. The terminal voltages have a defined operating range of 11 V$\leq$ V_{14} $\leq$ 16 V and 30 V $\leq$ V_{42} 50 V. The reason for the voltage range being considered instead of just the nominal operating point is that the voltage levels in the passenger vehicle fluctuate significantly and specifications must be met over both voltage ranges.

Fig. 5 shows the RMS current in C_{14} for a three-phase system on the left and a four-phase system on the right. Two observations can be made. The first is that under ideal conditions of V_{14} $=$ 14 V and V_{42} $=$ 42 V, there is no current in C_{14} for a three-phase system, while for the same operating point in the corresponding four-phase system, there is approximately 1.3-A RMS in the capacitor. The second observation is that the maximum RMS current in the capacitor occurs in the three-phase system compared to the four-phase system. There is just over a 25% reduction in the maximum current of a four-phase system compared to the three-phases system in C_{14}.

Fig. 6 shows the same plots but for C_{42}. In the figure, the RMS current in C_{42} for a three-phase system is plotted on the left and for a four-phase system on the right. As in the case with C_{14}, the maximum current over the voltage operating range is higher in the three-phase system than in the four-phase system. The maximum current in C_{42} is just over 25% lower in the four-phase system compared to the three-phase system. The RMS currents in C_{42} are significantly larger than in C_{14} so a reduction of 25% is considerable. Additionally, Fig. 6 shows that in a three-phase system operating at the nominal voltages, the RMS current in C_{42} is a minimum. But even the slightest change in V_{14} or V_{42} results in a large change in the capacitor RMS current.

Fig. 5 and Fig. 6 show that by correctly selecting the number of phases in an interleaved system, the RMS currents in the bus capacitors and thus their stress can be significantly reduced. The reduced RMS currents in the passive components can result in physically smaller components being able to meet the converter design specifications thereby helping to increase the power density.

B. Component Miniaturization Through Thermal Management (Thermal Design)

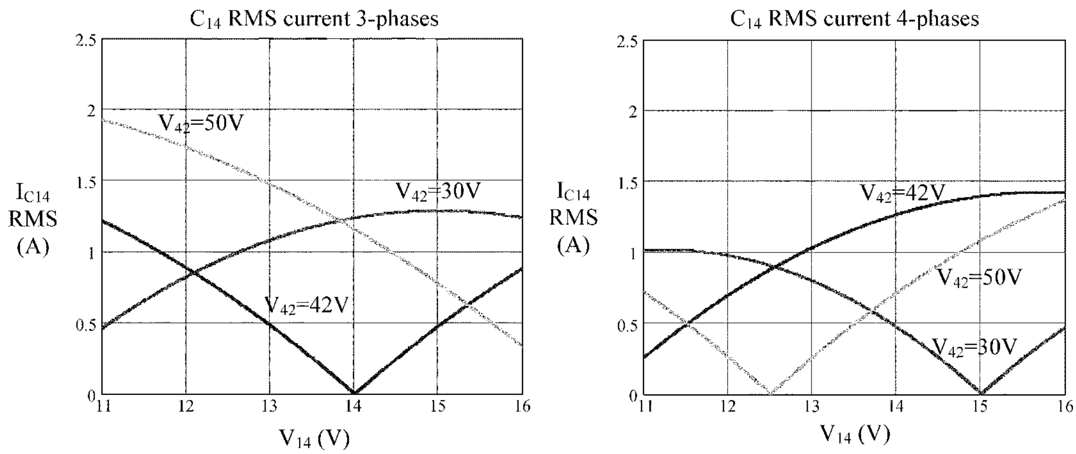
A second method to reduce the volume of a component is to significantly improve the thermal management of the component. The improved thermal management will reduce the temperature drop between the component hotspot and the heatsink. If the original temperature drop is desired but with the improved thermal management, then the loss density of the component must be increased. The increased loss density can be achieved by maintaining the excitation level and reducing the components volume within material limitations [12].

For example, improving the thermal management of the inductors implemented in the automotive converter can be achieved by integrating the inductors into special heatsink structures called integrated heatsinks [9], [10], [12]. These structures are used to place the inductors in the third dimension

$$I_{C_{14}}\,\mathrm{RMS} = \frac{\mathrm{V}_{42}T}{\sqrt{12L}}\left[\mathrm{ND}-(n-1)\right]\left[\frac{n}{N}-D\right] \qquad \text{for } \frac{n-1}{N} < D \leq \frac{n}{N} \tag{1}$$

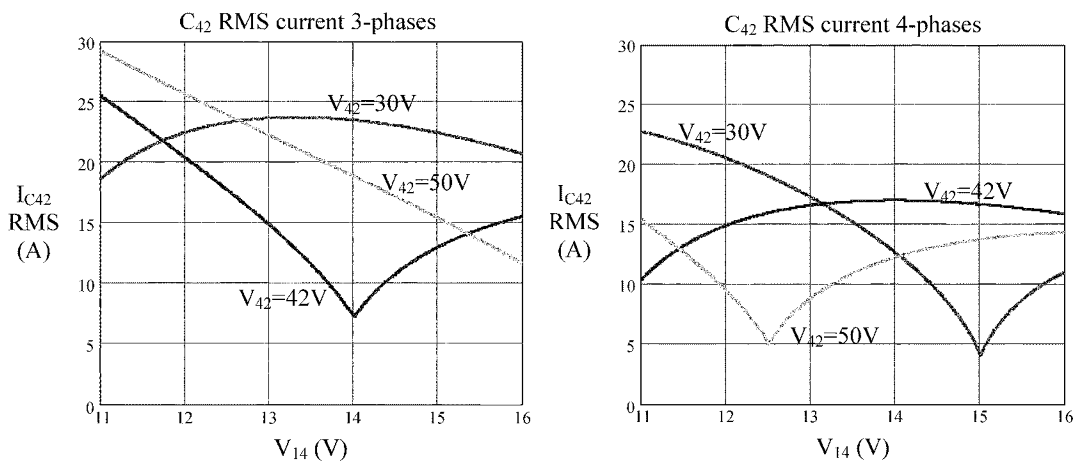
$$I_{\mathrm{C}_{42}}\mathrm{RMS} = \sqrt{\frac{I_{42}^2}{D^2}\left(D-\frac{n-1}{N}\right)\left(\frac{n}{N}-D\right)+\left(\frac{\mathrm{V}_{42}(1-D)DT}{L}\right)^2\frac{N}{12}\left[(n-1)^2\left(\frac{n}{N}-D\right)^3+n^2\left(D-\frac{n-1}{N}\right)^3\right]}$$
$$\text{for } \frac{n-1}{N} < D \leq \frac{n}{N} \tag{2}$$

$$I_{\mathrm{L\_RMS}} = \sqrt{\left(\frac{I_{42}}{\mathrm{ND}}\right)^2+\frac{1}{12}\left(\frac{\mathrm{V}_{42}(1-D)DT}{L}\right)^2}. \tag{3}$$



(a) (b)

Fig. 5. (a) RMS current in C_{14} as a function of the V_{42} and (b) V_{14} terminal voltages for a three- and four-phase 2-kW dc/dc converter.



(a) (b)

Fig. 6. (a) RMS current in C_{42} as a function of the (a) V42 and (b) V14 terminal voltages for a three- and four-phase 2-kW dc/dc converter.

above the bus capacitors or switching devices, as well as to remove the heat from the component with a small ΔT. An example of this structure is illustrated in Fig. 7. In the figure, the inductor is mounted in a heatsink with the inductor windings clamped in the heatsink (electrically isolated). The inductor windings are clamped so that the current density can be significantly increased without a large increase in the temperature drop between the inductor and thermal interface. There are two heatpaths connecting the inductor structure to the thermal interface to transport the heat dissipated in the component to the thermal interface [9], [10].

To avoid reliability issues and to improve the inductors thermal performance, the heatsink structure in which the inductor is mounted in must be dimensioned so that there is a small gap between the component and the heatsink. This gap is filled with an interfacing material that has good thermal conduction properties while providing the required electrical isolation. Further this material must be compressible. Due to the different coefficients of thermal expansion, mechanical stresses can exist in the different materials if room for expansion is not included. The compressible interfacing material between the component and heatsink prevents these stresses from arising while providing good thermal interfacing between the different

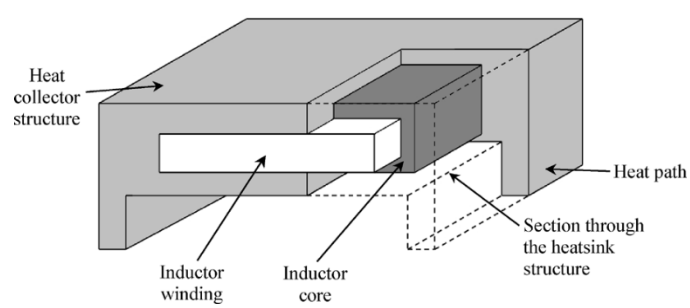


Fig. 7. Inductor mounted in a thermal management structure used to collect and transport all the dissipated heat down to the thermal interface.

irregular surfaces of the component and heatsink. Such materials are available from several manufactures (Chomerics: Therm-A-Gap G570 is an example).

Increasing the current density in the inductor windings, for a fixed amount of stored energy (assumed to be in the air gap), a fixed maximum magnetic flux density and a fixed thermal management results in a decrease in the inductors volume. Fig. 8 shows the reduction in volume of an inductor as a function of the current density in the inductor winding normalized to that of an inductor, storing the same energy and with the same thermal

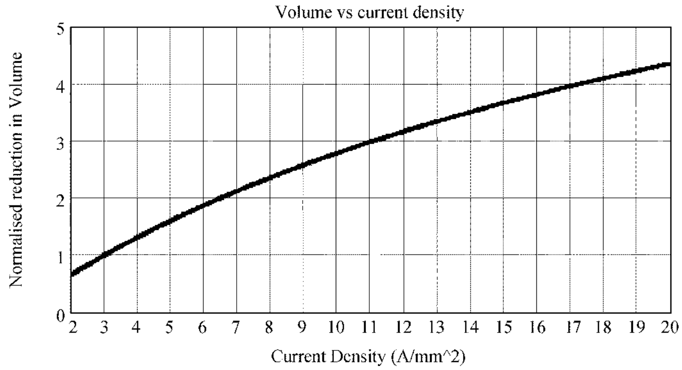


Fig. 8. Reduction in the volume of an inductor as the current density is increased for fixed amount of stored energy normalized to an inductor with a current density of 3 A/mm^2.

management but with a current density of 3 A/mm^2. A current density of 3 to 6 A/mm^2 is considered conventional for inductors [14]. As the current density increases, the loss density of the component also increases. The thermal management structure, specifically through the winding clamps reduces the thermal resistance so that the temperature drop between the component and thermal interface remains acceptable.

Using this thermal management structure, an inductor with a current density of 17 A/mm^2 was constructed and experimentally demonstrated a temperature rise of less than 10 °C between the inductor hotspot and the thermal interface [9]. From Fig. 8, it can be seen that the volume of the inductor with a current density of 17 A/mm^2 is four times smaller than an equivalent inductor of the same specifications but with a current density of 3 A/mm^2 (with the same core and winding window aspect ratio).

C. Component Placing and Geometric Manipulation

Two methods of reducing the volume of passive components have been considered. However, to achieve a high power density, all the miniaturized components must still be arranged in space in as small a volume as possible together with their interconnections.

To illustrate this, lets consider the implementation of one phase of a multiphase topology using the phase arm described in Fig. 4. Per phase there are two MOSFETs, one inductor, and one decoupling capacitor. The decoupling capacitor does not represent the full bus capacitance but contributes to the total bus capacitance C_{42}. The total bus capacitance is the sum of the bulk energy storage capacitance and all the decoupling capacitors capacitance. The decoupling capacitor is required to keep the voltage overshoot across the switching devices within specification.

The two MOSFETs are implemented on DBC in open die form. This form of device packaging is selected because of the improved thermal performance of the devices over conventionally packaged devices as well as volume benefits. To keep the voltage overshoot across the switching devices within specification, the loop between the two mosfets and the decoupling capacitor must be kept to an absolute minimum to minimize the inductance between the devices and the decoupling capacitor. This is illustrated in Fig. 9. A large decoupling capacitor is

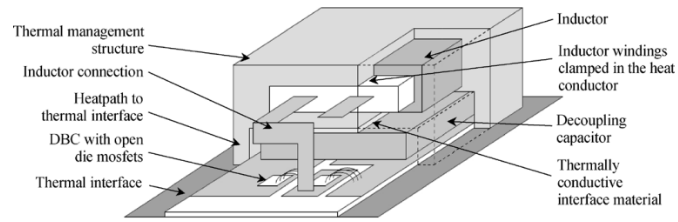


Fig. 9. Possible assembly of a phase in a multiphase system showing the phase arm components and interconnections.

required because as the number of phases increase, the inductance between the phase decoupling capacitor and the bulk bus capacitor will increase as their physical separation increases. If the phase inductance is implemented with the structure illustrated in Fig. 7, then it can be placed above the capacitor with the inductor winding connection directly above the mid-point between the two mosfets.

Fig. 9 shows that to package the four components in a small volume, the component dimensions must be chosen to complement each other. For example, the inductor structure can be used to help remove heat dissipated by the decoupling capacitor if it is in thermal contact with the capacitor through an thermal interfacing material. This requires the bottom of the inductor structure to be in close contact with the capacitor. Further, the width of the decoupling capacitor largely determines the width of the inductor structure and the mosfets location. From this it is evident that the choice of the decoupling capacitor has a large effect on the inductors maximum dimensions.

The volume of the components is also constrained by the heat dissipated in each component together with that components thermal management. It is therefore also possible to optimize the phase arms volume by distributing the losses between the components and allocating more heat to components where the heat can be removed more effectively if this results in a volumetric benefit. For example, increasing the losses in the inductor by increasing the current density in the winding window where it can be effectively removed is permissible if doing this results in an improved volumetric and geometric match with the decoupling capacitor.

Thermal interfacing is important in such a high density construction if all the components are going to function correctly. Just as in the case of the inductor, a compressible interfacing material should be used between any hard irregular surfaces in the implementation of the phase arm. This ensures electrical isolation, provides good thermal interfacing while at the same time removes the reliability issues that could arise due to different coefficients of thermal expansion. It is also possible to further improve the thermal management by displacing the remaining air in the construction with a thermally conductive paste or jell.

V. Case Studies

The two implemented case studies are both high power density dc/dc converters. The first case study is the first generation prototype capable of operating with a thermal interface temperature of up to 85 °C. The second case study is the second generation prototype capable of operating with a thermal interface temperature of up to 110 °C. Both prototypes are implemented with interleaved synchronous rectified phase arms as illustrated in Fig. 4.

In this section the two prototypes are briefly discussed in terms of their geometrical construction to illustrate how the electrical, thermal and mechanical designs have been integrated to meet the required specifications. The two prototypes are evaluated and the differences between them discussed. Detailed analysis, design and constructional information concerning the prototypes can be found in references and is not repeated.

A. First Generation Prototype

The first generation prototype was designed for a maximum thermal interface temperature of 85 °C and a power level of 2 kW. The converter is implemented with three interleaved phase arms sharing common bus capacitors at the terminals of the converter. The six-gate drives of the converter are also integrated into the structure. The converter operates with a switching frequency of 170 kHz per phase. The switching frequency was not selectable but given as a requirement. For a complete description and analysis of the converter see [10] and [11].

Fig. 10 shows a simplified cross section through the first generation converter showing the relative positioning of the phase arm inductor, the bus capacitors and the switching devices. A closed view of the implemented converter structure is shown in Fig. 11. The converter uses the interleaving of the three phases together with the fact that the input to output voltage ratio is 3:1 in buck mode to significantly reduce the requirements of the bus capacitors. Since the RMS currents in the bus capacitor are a minimum in this configuration, only a small bus capacitor is required to meet the voltage ripple specification. As the bus capacitors are small they are implemented within the converter structure with the parallel connection of several metal film capacitors to create the desired capacitor shape. The three custom planar inductors are mounted in thermal management structures, similar to Fig. 7, alongside each other to place them in the third dimension above the bus capacitors and switching devices. The thermal management structure of the inductors is then also used to remove the heat dissipated in the bus capacitors and transport it to the thermal interface. The semi-conductors are implemented with open die devices mounted on DBC and connected to the gate drives in the front of the structure. The multipin adapter in the front of the converter in Fig. 11 is used for measurements and connection to the gate drivers.

B. Second Generation Prototype

The second generation converter was designed to operate with a higher thermal interface temperature of 110 °C and over a larger voltage range than the first generation converter. To meet the extended specifications, the second generation converter was implemented with four interleaved phases of the same topology (the synchronous rectified buck) and has aluminum electrolytic bus capacitors integrated into the high power density structure. The complete control system together with the gate drives are also integrated into the high temperature structure. The complete description of the converter can be found in [12].

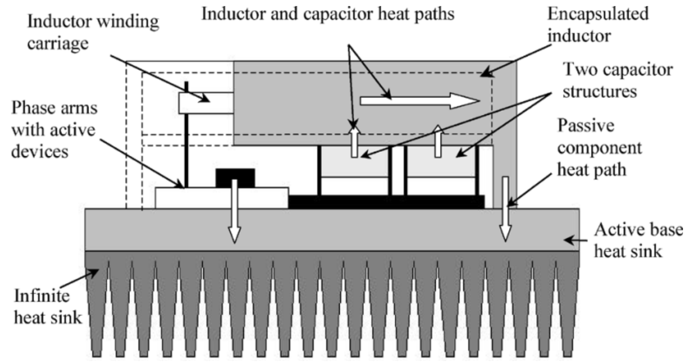


Fig. 10. Basic construction of the first generation prototype.

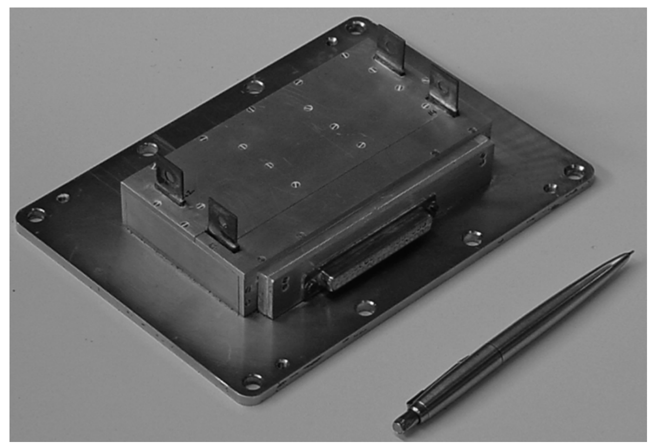


Fig. 11. First generation high temperature, high power density dc/dc converter.

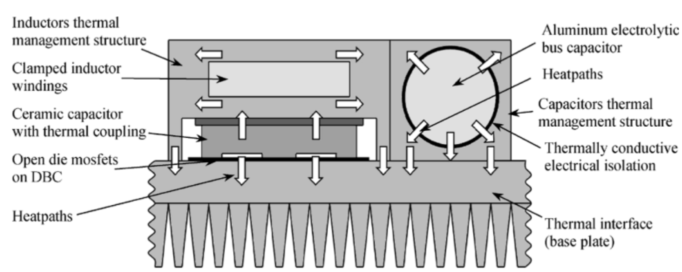


Fig. 12. Simplified cross section through a part of the second generation automotive converter.

Fig. 12 shows a simplified cross-section through one of the four phases implemented in the converter together with the heat paths between the heat sources and the thermal interface. The figure shows the phase arm inductor mounted in a thermal management structure with the thermal management structure in contact with a ceramic decupling capacitor mounted on the DBC directly behind the open die mosfets. This construction is illustrated in Fig. 9. Additionally, an aluminum electrolytic capacitor is mounted horizontally next to the phase inductor. Due to the higher RMS currents in the bus capacitances, the bus capacitors are implemented with a parallel combination of aluminum electric capacitors and ceramic decoupling capacitors. The 42-V bus capacitor for example is implemented with the parallel combination of two aluminum electrolytic capacitors and four ceramic decoupling capacitors. Both the electrolytic and ceramic capacitors are high temperature devices with the electrolytic capacitor rated for a maximum temperature of 150 °C (Epcos B41693)

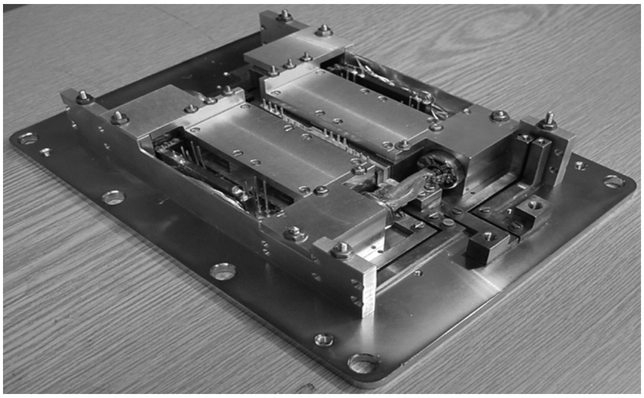


Fig. 13. First generation high temperature, high power density dc/dc converter.

TABLE I
COMPARISON BETWEEN THE FIRST AND SECOND GENERATION PROTOTYPE PROPERTIES

Parameter / Property	1st Generation Prototype	2nd Generation Prototype
Power density	170W/in^3	120W/in^3
Maximum thermal interface temperature	85°C	110°C
Number of interleaved phases	3	4
Switching frequency per phase	170kHz	140kHz
EMI filters	Simple LC common mode filters	Integrated LC filter common and differential mode filter structures
Control	Integrated gate drivers	Integrated controller and gate drivers
Operating voltage range	14V / 42V	11V-16V / 30V-50V
Power rating	2.1kW	2kW
Inductors	2.2μH (2 turn planar inductors)	3.8μH (7 turn planar inductors)
Capacitors	Metal film as decoupling and bus capacitors	Ceramic decoupling and aluminium electrolytic bus capacitors
Inductor Volume (active material)	Per inductor: 17199mm^3 Total inductor: 51597mm^3	Per inductor: 4040mm^3 Total inductor: 16160mm^3
Capacitor volume (active material)	Decoupling and bus: 8390mm^3	Decoupling: 8181.6mm^3 Bus: 19697mm^3
Total passive volume (EMI filter excluded)	59987mm^3	44040mm^3

and the ceramic capacitors, 160 °C (Novacap "G" dielectric). The aluminum electrolytic capacitor is mounted horizontally to maintain a low profile and in a thermal management structure similar to the phase inductance to remove the heat dissipated in the component. Heat is removed from the bus capacitors both radially and axially to minimize the components temperature rise. The second generation prototype is photographed in Fig. 13 with some of the thermal management structure and the control system removed to reveal the structure of the converter. The bottom right is the 42-V connection while the top left is the 14-V connection. The four inductors are mounted in the centre of the converter with the high voltage bus bar running down the centre of the structure.

A three phase topology was not selected for the second generation converter because the volume and the losses in the bus capacitors would be too large over the full operating voltage range. The second generation converters specifications require the converter to operate with a high side voltage from 30–50 V and a low side voltage of between 11–16 V instead of just 42 V and 14 V, respectively. The four-phase topology was selected to reduce the RMS currents in the bus capacitors allowing the aluminum electrolytic capacitors to be integrated into the converter structure.

VI. Comparison and Evaluation

The primary characteristics of the two converters are tabulated in Table I. From the table it can be noticed that the power density of the first prototype is 30% higher than for the second prototype. However, the functionality and the efficiency, plotted in Fig. 14, of the second prototype is significantly higher. The second prototype operates with a higher maximum thermal interface temperature, while integrating the aluminum electrolytic bus capacitors and the control into the structure. An increase in the functionality results in a decrease in the power density. The two prototypes also operate with different switching frequencies. The switching frequency was part of the given converter specifications and was not considered as a variable for optimization.

The volume of the inductors, the bus and decoupling capacitors are also listed in the table. The table shows that the total volume of the passive components (only electromagnetically active materials, not the thermal management structure) in the second generation converter is approximately 26% smaller than that of the first generation converter even through there are four phases. The reduction in volume is due to the reduction of component stresses through interleaving and the thermal management structure. The reduced component stresses reduce the losses in the components for a given specifications while the improved thermal management structure removes the heat dissipated in the components with a smaller temperature drop between the heat source and thermal interface.

The primary difference between the two prototype converters, other than the number of phases is that the second generation prototype includes the aluminum electrolytic bus capacitors in the design. The first generation prototype operates well at the defined operating point of 14/42 V. But if either voltage is slightly different, then the losses in the structure increase significantly because the capacitors in the structure are severely overloaded. This is also evident from Figs. 5 and 6 for three phases. Any change in the duty cycle, however small results in a very large increase in the capacitor RMS currents. Further, the second generation converter is designed to operate over a voltage range where the capacitor currents are not at their minimum over the entire operating range, making the electrolytic capacitors a necessity. The electrolytic bus capacitors are successfully integrated into the high temperature structure by minimizing their RMS currents through interleaving and minimizing their operating temperature through thermal management.

The measured efficiency of the two prototypes is plotted in Fig. 14. The graph on the left is for the first generation prototype while that on the right is for the second generation. For both converters it is clear that the efficiency decreases as the thermal interface temperature increases. This is due to the thermal dependence of the losses in the various components. It is also clear that the efficiency of the second generation prototype is higher than that of the first generation over the complete operating range. The efficiency in the second generation converter

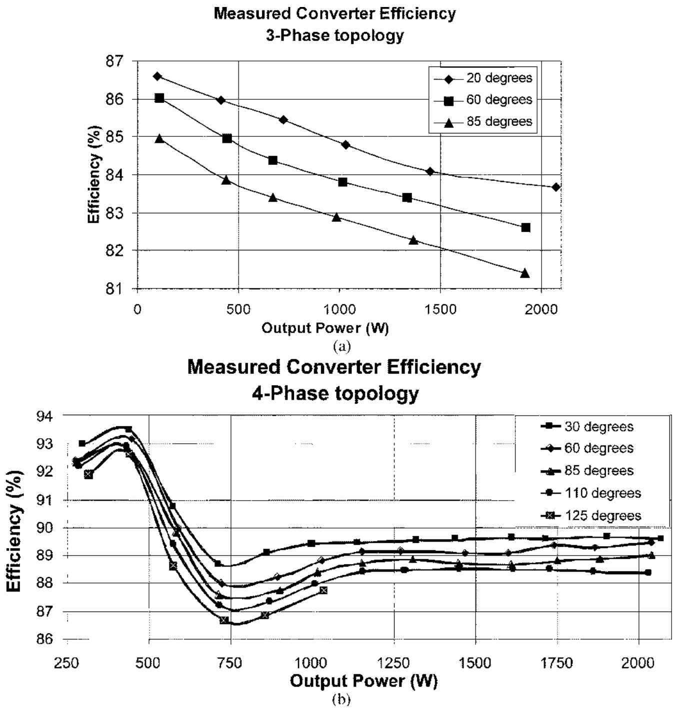


Fig. 14. Measured efficiency as a function of the thermal interface temperature for the (a) first and (b) second generation prototype converters for 14/42 V operation.

also shows a significant drop at around 500 W delivered power. This is the point where the converter passes through discontinuous mode into continuous mode. In discontinuous conduction mode the topology does not suffer reverse recovery losses resulting in a higher efficiency. As soon as the topology begins to operate in continuous conduction mode, the freewheeling diode experiences reverse recovery resulting in a significant increase in the converters switching losses reducing the efficiency.

VII. Technological Issues

Of the technology issues encountered, 3-D interconnections that are capable of high current densities at high temperatures to connect the inductors and bus capacitors to the open die mosfets is one of the most limiting factors. The mosfets are implemented on DBC, so reliable connection between the passive components and the DBC are required. Currently, in the first prototype, interconnection between the inductors and the DBC is implemented with copper conductors soldered into place by hand. This type of interconnection is difficult to implement. The second prototype uses conductive pillars that are soldered onto the DBC during the semiconductor soldering phase and then soldered to the inductor. This interconnection has several advantages over that used in the first prototype with the main one being the automated process. Both methods currently used to implement these connections are labour intensive, contribute to the converters volume and are costly. For 3-D packaging to become more viable, simpler and easier to implement interconnections between the active and passive components are required.

The thermal management technique discussed in the paper is extremely effective but is costly to implement. The various parts all need to be machined making the structure labour intensive. Further, since all the thermal management parts are machined, detailed drawings of every part are required. Simpler methods of implementing the thermal management structure are required. Possibilities include alternative materials and moulding.

VIII. Conclusion

In this paper, an integral thermal, electrical and mechanical design for a high power density converter operating in a high ambient temperature (automotive) environment is considered and demonstrated. The interaction between the thermal, electrical and mechanical design is considered and is shown that instead of the interdependencies being a limiting factor, they can be used to an advantage to help achieve the final high temperature, high power density design.

To meet the power density and the temperature requirements of the automotive converter, circuit and structure manipulation techniques are required to reduce and redistribute the converters losses, and to remove the dissipated heat effectively and with as small a temperature drop as possible. Two such techniques are considered, namely interleaving and the integrated thermal management structure. Interleaving, an electrical circuit manipulation technique, is used to reduce the losses in the passive components by reducing the RMS currents in the components. This results in smaller bus capacitors and smaller inductors. The thermal management structure, a thermal circuit manipulation technique, is then used to further reduce the volume of the various passive components by removing the heat dissipated in the component very effectively. Once the volume of the various components has been reduced, the components must be assembled in a structure that minimizes the unused volume between the components. This can be achieved by designing the shape of the various components to complement each other and to fit tightly together.

Two generations of high power density dc/dc converters are considered to illustrate the integral design. The first generation has a maximum thermal interface temperature of 85 °C with a power density of 170 W/in^3 while the second generation has a thermal interface temperature of 110 °C and the power density of 120 W/in^3. The second generation prototype also has a higher efficiency than the first as well as a much higher functionality.

In the implementation of the prototypes, technological limits were encountered. Of these limits, the high current density three-dimensional interconnections between passive components was the most limiting to the volume. This area of interconnection technology is identified as one that needs attention for the future development of integrated power electronic structures.

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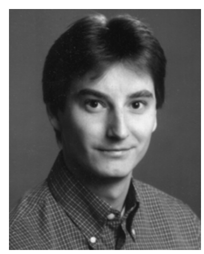

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