OPTIMIZED SELECTION OF MATERIALS AND COMPONENTS FOR POWER MODULE REALIZATION

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Key words: materials and components, power module, power module performance

Abstract: Most simple electrical traction systems consist of an electrical motor, a power module and an electrical energy source. The power module converts electrical energy supplied by the battery source into suitable power signals required for driving the electrical motor. The power module is usually realized with semiconductor power switches (e.g. MOSFET transistors) which are used for driving electrical loads of up to 10kW and more. To achieve power module electrical and mechanical requirements the materials and components of the power module must be carefully selected. The materials and components proposed for the power module have a direct effect on the overall system performance and on the price/performance ratio. In this paper we focus on the properties of materials and components and their optimal selection. With proposed materials and components, some modifications of technology processes of the power module construction were put in effect. With the proposed materials, components and a new power module design the price/performance ratio achieved was 1.6 times higher compared to the state-of-the-art power module realizations currently available in the market.

Izbira optimalnih materialov in komponent za izvedbo močnostnega modula

Kjučne besede: materiali in komponente, močnostni modul, izkoristek močnostnega modula

Izvleček: Močnostni moduli služijo za pretvorbo električne energije akumulatorja v ustrezne električne signale za krmiljenje električnih motorjev vgrajenih v električnih pogonskih sistemih. Močnostna stikala modulov so najpogosteje realizirana z močnostnimi polprevodniškimi elementi (npr. MOSFET tranzistor), s katerimi je možno krmiliti električna bremena do 10kW in več. Za doseganje električnih in mehanskih lastnosti - zahtev močnostnih modulov je potrebno posebno pozornost posvetiti optimalni izbiri uporabljenih materialov in komponent. S prikazano realizacijo močnostnega modula ter s predlaganimi materiali in komponentami je dosežen cilj zvišanja faktorja cena/učinek. V tem članku je poudarek na izbiri materialov z optimalnimi lastnostmi in komponent za realizacijo močnostnega modula, prikazane pa so tudi potrebne izboljšave in prilagoditve tehnoloških procesov, ki so uporabljeni za samo realizacijo močnostnega modula. S predstavljenimi materiali, komponentami in novo zasnovo realizacije močnostnega modula, je doseženo razmerje cena/učinek za 1.6 večje kot pri obstoječih rešitvah na trgu.

1. Introduction

The power modules built in electrical traction systems can be used for driving a diverse range of electrical motors or loads. For driving a three phase electrical motor the power module is realized as three branches in parallel connection where each individual branch is used for driving a single phase of the motor. Each branch is realized in the form of as two independently controlled switches connected in serial between battery terminals. The middle point of two switches is connected to the motor phase terminal. The switches are used to connect the motor phase either to the positive or the negative battery terminal. The power module switches are usually realized with the semiconductor power devices (e.g. MOSFET, IGBT) the switching action of which can be controlled with external logical circuit. Each switch state is controlled with external circuitry, usually controlled with an additional DSP. The DSP has a built-in algorithm for driving each individual switch in all three branches. The DSP algorithm is determined with the application of the electrical traction system.

Performance of the electrical traction system is influenced by each construction part of the system. In this article the focus will be on the power module's electrical and thermal performance. The power module is connected between the power supply battery and electrical motor as shown in figure 1.

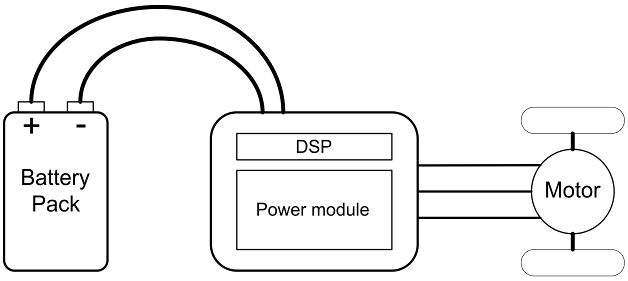

Fig. 1: Electrical traction system

Performance of the power module is - beside properties of semiconductor switches - also affected by the selection of the optimal materials and components of the power module's construction and its design. To achieve high performance of the power module the construction materials and components must be carefully selected. Some aspects for future design approaches of the power module realizations are presented in /1/. The selection of the materials and components has to meet electrical, mechanical and thermal requirements of the power module. With the selection and use of the proposed materials and components in the power module, construction should also be subjected to achieving a higher price/performance ratio. To make the best use of the proposed materials and components the design and construction of the power module requires development of some new technological approaches and modifications of existing microelectronics and PCB manufacturing technologies.

2. Selection of materials and components

The design and material selection of the power module construction parts should be subjected to fulfilling the goal of the final realization achieving high performance at reasonable costs. The requirements can be divided into several categories. Each group of these requirements should be met and taken into account during the power module's design.

2.1 Electrical requirements

Electrical requirements of the power module's design should pursue the goal of keeping the parasitic influences as low as possible. At this point the designer of the power module has to consider two major types of parasitic influences: parasitic contact resistances and parasitic inductivities. Both influences have a direct effect on the power module's performance. The source of the here mentioned parasitic influences can be found in immediate correlation with the materials used in the construction parts of the power module's realization. An important source of the parasitic influences is geometry of the construction parts and the power module's design, which will not be discussed in detail. More detailed power module design considerations and measurement results are also presented in certain previous works /2/, /5/, /6/ and /7/.

Designer's first concern is to minimize the parasitic contact resistances which contribute to the power module's efficiency and consequently also to its thermal performance. Special attention must be paid to optimizing the contact resistances between the power MOSFET transistor terminals and a busbar, and contacts between busbars of equal voltage potential /2/, /7/. The selection of the busbars material plays an essential role in providing low contact resistances between busbars. To ensure low contact resistances between busbars the design geometry of the busbars should be carefully carried out. The surfaces of the busbars where the electrical contacts are realized should be designed so that sufficient high mechanical pressure between two contact surfaces of connected busbars can be applied. Figure 2 provides an example of how two construction parts can be mechanically fastened. Ensuring contact with mechanical fastening of two construction parts has an important influence on the electrical and thermal performance of the power module.

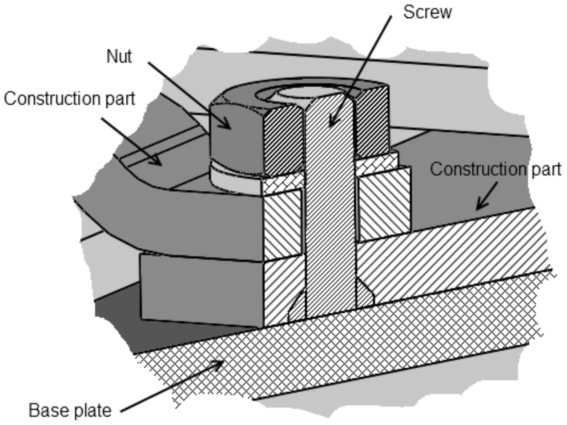

Fig. 2: Example of mechanical fastening of two construction parts

The second group of parasitic influences which directly affect the power module's performance are the parasitic inductances. The origin of the power module's parasitic inductances is related to the power module's construction and to materials used in the construction parts. Efficiency of the power module where parasitic inductances are present is affected when the switching transitions of high currents are performed. The equation (1) gives a rough estimate of how high the induced voltage can be when 400Amps are switched in 400nsec time, with parasitic inductance of 10nH.

$$u_L = L\frac{di_L}{dt} = 10\cdot 10^{-9} H \frac{400A}{400\cdot 10^{-9} s} = 10V \qquad (1)$$

The inducted voltage of 10V could present serious influence on the semiconductor power MOSFET transistors and performance of other electronic components. When designing the power module the designer should consider EMI legislation for the specified power application. More detailed studies of the power module construction were presented in /3/, /4/, /7/.

2.2 Thermal requirements

To ensure stable operation and adequate lifetime of the power module the heat dissipation generated within the power module must be kept to minimum and controlled so that it does not exceed the maximum allowable operating temperature. The power losses conducted within the power module generally manifest in higher working temperatures of the power module /6/. Consequently, with higher temperatures, the losses on the power MOSFET transistors and busbars increase which affects the power module's performance. To prevent the degradation of the power module's performance due to high temperature the power module should be designed in a way that the conducted thermal losses are efficiently transferred to the cooling body.

The power modules are usually mounted on the vehicle and therefore the modules are exposed to several ambient influences (e.g. temperature changes, vibration, corrosion, etc.) in their lifetime period. In case of improper selection of the materials and components the mechanical stress can lead to lower performance or, eventually, also to failure of the power module. Selection of the optimal materials and components should be subjected to satisfying the required properties of the power module and also to getting higher price/performance ratio.

2.3 Mechanical requirements

Electrical traction systems installed in vehicles are usually exposed both to the ambient conditions and to mechanical stress. Beside temperature and humidity changes the power module also has to withstand stress caused by vibrations. In this article we will not pay detailed attention to mechanical/environmental requirements of the power module which are different in each specific application.

3. Properties of materials and components used in power modules

The power module switches are realized as in parallel connected semiconductor devices which are capable of controlled switching of high current densities. The performance of each switch depends on two main factors. The first factor refers to the quality of the electrical connections of the semiconductor power device while the second very important factor is the way in which conducted heat dissipation of the device is transferred to the attached heat sink. The most common approach of attaching the semiconductor power device is the attachment on the PCB. For lower power application commercially available standard PCB substrates are usually used (e.g. FR4). The middle power range applications require more sophisticated substrates with better thermal performance, such as IMS /8/, /9/. Advanced power application requires the use of high quality substrates which have excellent electrical and thermal properties. In such application often a DBC substrate (Direct Bonded Copper) is used, basically because of its high thermal conductivity /10/. On the figure 3 DBC and IMS substrate structure, together with their corresponding cross-sections, are presented.

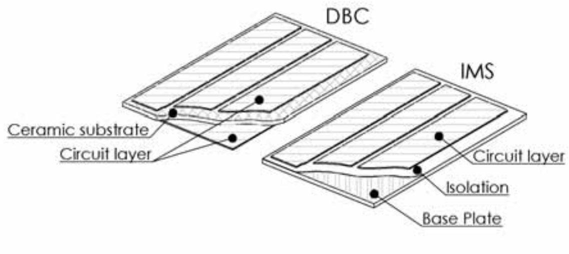

Fig. 3: DBC and IMS substrate structure

The DBC material is a "sandwich" structure where a ceramic substrate is placed between two copper layers. The detailed structure of power module construction with DBC substrate is presented in /6/. Because of the DBC substrate's main advantages in comparison to other substrates, such as low thermal resistivity, low thermal expansion, high voltage isolation and high working temperatures, the DBC substrate is widely used in power applications.

The main drawbacks of using the DBC substrate in power module realizations are the limited ability of the mechanical fixture of the DBC substrate to the heat sink, relatively thin circuit layer, substrate processing and price. To ensure good thermal contact between the DBC substrate and the heat sink, sufficient mechanical surface pressure through the entire substrate area must be establish. In some cases such requirements cannot be easily achieved. The source of the DBC substrate's mechanical fixture limitations can be found in the mechanical properties of the ceramic layer (e.g. Al_2O_3). In applications where high current densities are conducted the DBC substrate is limited with the circuit layer thickness which is manufactured only up to 300um.

The IMS substrate consists of three layers: conductive layer, insulation layer and base plate material. Top conductive layer is usually made of by a thin layer of copper which is used for electrical circuit realization. Also available on the market are IMS substrates with more than one circuit layer which enables the realization of multilayer and more complex PCB board. On the other side, thermal performance is affected because of one or more additional insulation layers. Between the conductive layer and the base plate an insulation layer can be found which is used for electrical insulation. The base plate is usually made of highly thermal conductive metal (e.g. copper, aluminium) and is used for two main aspects: first to provide good thermal contact with the heat sink and second provide solid physical support for the busbars or any other electronic-mechanical parts. In Table 1 properties of DBC and IMS substrate as well as standard PCB FR4 material are presented.

Table 1: Properties of DBC, IMS and FR4 substrate

Properties	DBC	IMS	FR4
electrical	good	excellent	excellent
thermal	excellent	good	poor
mechanical – fixture	good	excellent	good
price	high	medium	low

As Table 1 indicates the DBC substrate is the best substrate regarding thermal properties. But the bottleneck of the DBC substrate, compared to the IMS, can be found in its electrical and mechanical properties as well as in its price. The FR4 substrate possesses excellent electrical properties and comes at acceptable price but its thermal properties make it unsuitable for a high performance power application, where good thermal transfer to the heat sink is required.

4. Power module construction

With the selection of proper materials and components and with the proposed power module construction /4/ the performance cost ratio is improved (compared to the previously proposed art solutions). In the previous art solutions the semiconductor power transistors are soldered or sintered directly to the conductive circuit layer of the used substrate. The main limitation of this solution is in the limited thickness of the circuit layer which is determined by the manufacturing process of the DBC substrate. Another limitation is the realization of the mechanical fixture options for assuring good thermal contact to the heat sink.

To achieve a higher capability of conducting higher current densities the conductive circuit layer has to be modified. This can be achieved with two different approaches. The first approach is to replace the conductive circuit layer material with a material which has a higher specific electrical conductivity. Our other option, beside the possibility of replacing circuit layer material (e.g. silver instead of copper), is to increase the circuit layer thickness. Currently available conducting layer thicknesses on the market range up to approx. 350um.The second approach for increasing electrical conductivity of the circuit layer is implementation of an additional layer of highly electrical conductive layer (such as busbars), which is placed on top of the circuit layer. Such solution is shown in figure 4 below.

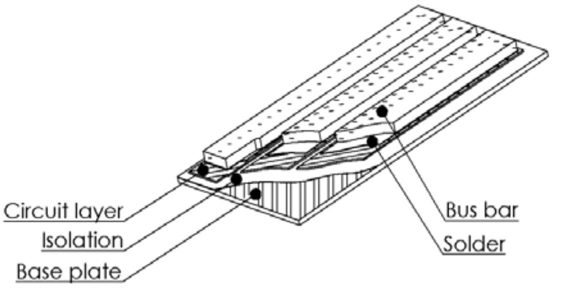

Fig. 4: The propose structure with IMS and busbars

The material used for a busbar should have high electrical and high thermal conductivity. The most suitable material is copper. The main advantage of a custom busbar, compared to DBC substrate copper layer, is in its ability to achieve lower resistance. Consequently, a thicker conductive layer, realized by a busbar, contributes to lower parasitic resistance and lower parasitic inductances of the power module. The internal power module connections (connections of the power devices and connections to external terminals) also have an important impact on the overall performance of the power module. The use of the busbar also offers the possibility of direct connection of the power semiconductor device terminals to the power module output terminal (e.g. to a motor phase cable), which – in case of using only the circuit layer – is difficult to achieve. In the proposed realization of the power module, the metal busbars are placed on the highly thermal conductive insulated metal substrate (IMS). The electrical and thermal contact between busbars and IMS circuit layer is realized with a layer of solder which has excellent electrical and thermal properties.

5. Thermal power module performance

Selection on improper materials and components for the power module, besides the power module's construction, can also reflect on the power module's thermal performance. For the purpose of qualifying the optimal materials and components proposed for the power module, thermal measurements of the realized power modules were performed. For evaluating the power module's thermal behavior, a series of thermal tests on three different power modules was performed. Besides the unique construction of each power module, the main difference was also the number of implemented semiconductor power devices. In our case MOSFET transistors were used. Testing conditions for all three power modules were the same: duration 1hour, AC motor phase current of 250Amps. In figure 5 temperature behavior for each individual DUT is shown.

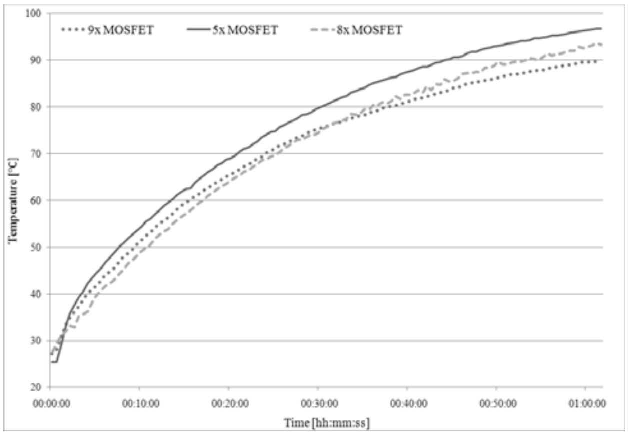

Fig. 5: Temperature measurement under working conditions of the power module with different number of implemented semiconductor power devices

The temperature behaviors shown in figure 5 indicate that after 1hour of operation the power module with the lowest temperature was the one with the highest number of MOSFETs. The power module proposed in this article is realized with 5x MOSFET transistors per individual switch. After 1 hour of testing the realized power module reached the highest temperature 94.6°C which is 6.8°C higher compared to the power module with 9x MOSFET and 3.5°C higher compared to the power module with 8x MOSFET. The performance ratio between the proposed power module and the power module with 9x MOSFET can be simply deducted and is approx. 1.6 times higher.

6. New construction approaches – assembly technologies

Besides the use of advanced material and components, construction of high performance power modules also requires employing new and advanced assembling technologies. Special attention was paid to electrical and thermal connection of the semiconductor power devices. From the electrical aspect of semiconductor power device connections special focus should be paid to the lengths of current paths and parasitic inductances' optimization. On the top, each semiconductor power device in die form is connected with bonding wires and on the bottom soldered directly to the busbar, as shown in figure 6 below.

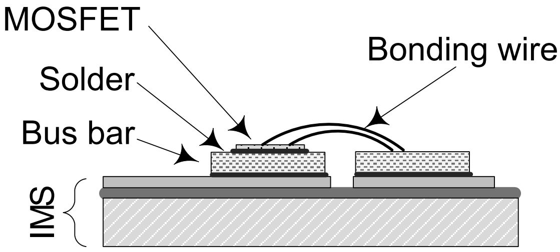

Fig. 6: Power module cross-section

To achieve excellent thermal contact between the parts used of the power module, an approach of direct soldering of the semiconductor power dies to the busbar and the busbar to the IMS substrate is used. This approach ensures excellent electrical and thermal properties of the assembly /4/, /7/.

7. Conclusion

The article focuses on the optimized selection of materials and components for the realization of a high performance power module. The use of proposed materials and components, together with the proposed power module structure, fulfills the goal of achieving the power module realization with a smaller number of semiconductor power devices. The presented electrical and thermal measurements indicate that, with the use of proposed materials, components and power module's design, a 1.6 times better performance was achieved, compared to similar power modules available on the market.

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