Optimization of Insulated Gate Bipolar Transistor System to Maximize Heat Dissipation

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Abstract. An electric motor, a battery and an inverter are the key components of any hybrid vehicle. The most commonly used switching device in the electric power conversion system is Insulated Gate Bipolar Transistor (IGBT) modules. Heat sinks with their fins are optimized to provide the maximum heat flow to the surrounding and Pure copper is used as it has high thermal conductivity with reasonable heat resistance. This helps to decrease the temperature of the IGBT and heat will spread to the fins. Parallel forced air cooling is utilised to give maximum possible heat removal rate. Further experimentation was done on a IGBT using an Inverter circuit and it was analyzed on ANSYS software and it was observed that the results obtained by numerical method and experimental method are approximately same.

Keywords: Heat Enhancement, Heat Sink, IGBT Model.

1. Introduction

An electric motor, a battery and an inverter are the key components of any hybrid vehicle. The electrical energy from the battery is supplied to the motor by with the help of inverter which is used as an electric power conversion system. Also it stores the energy generated by motor in the battery. The most commonly used switching device in the electric power conversion system is Insulated Gate Bipolar Transistor (IGBT) modules [1].

The switching device used in electric power conversion system i.e. IGBT is actually a semiconductor device having four alternating layers (P-N-P-N) which are controlled with metal oxide semiconductor gate structure without any regenerative action.

The increase in the device temperature which occurs when transient maximum current flows to the motor at the time of acceleration must be restricted in the acceptable range so that the performance advantage of power devices can be completely used. Moreover, electrical regenerative braking used at the time of deceleration collects the energy in the form of electrical energy which was previously emitted as heat energy from the hydraulic brakes that can be reused to improve the economy of fuel.

The most important thing is to collect the maximum amount of electric power throughout the small braking time from the commencement of deceleration to complete stopping. To achieve this the devices which are capable of conducting large amount of current within a very short duration are necessary.

Power semiconductor devices and modules are the key components of each power converter. [2] Insulated-gate bipolar transistor (IGBT) modules are commonly used for mid to high-power
applications such as electric vehicle inverters, because of their high voltage and current capability. IGBTs are key components in inverter design because the characteristics of the device determine the inverter behaviour and the periphery circuit.[4],[5]

2. CFD Approach for Design Optimization

2.1. Problem Definition

The aim to carry out the thermal characterization of IGBT (Insulated Gate Bipolar transistor) module for predict the maximum temperature. To find the optimized model of IGBT here carry out the parametric study of IGBT. In parametric study different parameters will be changed such as base plate thickness, substrate thickness, pitch of fins, square fins instead of circular fins, heat transfer coefficient, out of whichever is more sensitive to peak temperature in ANSYS Icepak.[6]

The model comprises an IGBT chip acting as a heat source. IGBT chip is dissipating 1000W of heat. To dissipate such a tremendous amount of heat it is accompanied with the substrate layer which contains the three layers, viz., Upper DBC, Ceramic substrate, Lower DBC, etc. The IGBT chip is sandwiched between two such substrate layers. Finally the substrate layer is provided with the heat sink at the end, to spread the heat effectively. To simulate actual working condition, two fans are provided. As the failure of any component of a model is a failure of a system as a whole. The solders are prime cause of the IGBT failure. The solder fails above 1800C. So, is required to maintain the temperature of source below 1800 C. There is no weight constraint. Fans can have the flow rate up to 1000 cfm.

To have even better heat spread to the surrounding, the heat sinks are incorporated. The details of the heat sinks are provided in the following section. Heat sinks with their fins are optimized to provide the maximum heat flow to the surrounding as shown in Figure 1. The material for the heat sink is selected accordingly. The fin count is also varied. As mentioned above the fans can have any flow rate not exceeding the 1000 cfm. The fans are in XY plane. The flow direction is along the Z-axis. The fans are intake-type. They take the air at ambient temperature.[7]

2.2. Geometrical Aspect

As the IGBT chip a very tiny structure having high flux density. The scope of this problem is limited to forced air convection. Hence the conventional approach of IGBT with the single substrate layer and heat sink dose not yield the satisfactory result. Hence the dual heat sink is used. The dimensions referred are initially put onto various layers and accordingly the CFD models are prepared and hence further analysis is done by applying various boundary conditions on them. The dimensions of the above layers are tabulated in following Table 1.
Table 1. Dimensions of Various Plate Layers

| Name of Plate       | Dimension     |
|---------------------|---------------|
| Base Plate 1        | 35mm X 35mm   |
| Solder 1.2          | 20mm X 20mm   |
| Lower DBC 1         | 20mm X 20mm   |
| Ceramic Substrate 1 | 25mm X 25mm   |
| Upper DBC 1         | 20mm X 20mm   |
| Solder 1.1          | 9.1mm X 9.1mm |
| Source              | 9.1mm X 9.1mm |
| Solder 2.1          | 9.1mm X 9.1mm |
| Upper DBC 2         | 20mm X 20mm   |
| Ceramic Substrate 2 | 25mm X 25mm   |
| Lower DBC 2         | 20mm X 20mm   |
| Solder 2.2          | 20mm X 20mm   |
| Base Plate          | 35mm X 35mm   |

There are heat sink as shown in Figure 2 attached at the end of the both the substrate layers. The heat sink dimensioning details shown in Table 2. There are two fans each having 370cfm in the XY plane to simulate the air flow. The flow is through Z plane.

Figure 2. Dimensions of Fin

Table 2. Dimensioning Details of Heat Sink

| Fin Details       |         |
|-------------------|---------|
| Thickness         | 1 mm    |
| Count             | 19      |
| Flow direction    | along the Z-Axis |
| Material          | Silver  |

| General Specifications |         |
|------------------------|---------|
| Time Variation         | Steady  |
| Variables Solved       | Temperature, Flow |
| Flow regime            | Turbulent |
| Heat Source            | Source1 (IGBT) |
|                        | Power = 1000W |
| Fan specifications     | Flow = 370cfm |
|                        | Diameter of Fan = 0.0675m |

2.3. Assembly of Complete Model

After complete assembly of all the components in the cabinet the final assembly as shown in Figure 3 and 4.
3. Experimental Setup of IGBT Model

The complete experimental setup is as shown in Figure 5. It consists of a Inverter circuit which has IGBT chip for amplification and conversion of the DC voltage into AC voltage for its application.
The chip gets heated if it is continuously run. So there was a requirement to optimize the cooling effect as shown in Figure 6 so that there might be no failure occurring of the chip. Thus the above designed fins are fitted on both sides of the IGBT chip so as to maximize the heat dissipation.[3]

Thus the results are taken initially for experimental model with 100W without any cooling effect provided. The heating of the chip is more, so fin is added on both sides of the chip and again the results are taken.[11] The results were taken on a temperature indicator shown in Figure 7 provided in the setup where the temperature of different points can be obtained and are illustrated in the results further, cooling is obtained by using a forced cooling system that is by making the use of fan as was done in the previous results. Thus the heat was dissipated effectively and thus this proved to be the best way for cooling purpose.
4. Result and Discussion

As the solders are in immediate vicinity of the source, they are in direct contact with the source hence are having the same maximum temperature. The CFD analysis of the problem yields following results.

4.1. Temperature Contours For 100W in CFD Analysis

Temperature contours of the important layers as shown in Figure 8. The hotness and coldness of the component is shown by relative intensity of the colors, where blue stands for the colder area while the red indicates the hottest area.

The temperature scale is provided in the right most corner. By analyzing the temperature contours, it is found that the maximum temperature of the model is 43.408°C at source as shown in Figure 9. As a matter of fact, the highest temperature was of the source and solder layers which are in the immediate vicinity of the source. Though the central portion is having the temperature around 41.029°C but it is being dominated by the region having temperature in the range of 38.651°C.

![Figure 8. 3D Model with Temperature Contour](image1)

The central red spot surrounded by the greener region indicates that heat is being spread in all the directions without much resistance. These are the contours obtained for 100W as per the experimental setup. It consist of an inverter circuit having a IGBT mounted on it so as to convert the DC voltage into a AC voltage of required amount.[8]

![Figure 9. 3D Model with Temperature Contour](image2)

This is not surprising since the substrate layers are doing exactly what they are supposed to do. The substrate layers are well below the safe temperature limit. Sandwiching the source in between the two substrate layers is actually having a remarkable effect on the heat dissipation. The edges of the layer are well below 35°C.
Figure 10. Temperature Contour in Fins

The middle ceramic substrate is having the temperature around 36.272°C. Base plate is last component in the IGBT cluster. The one that attaches the cluster with the heat sink. Being in the middle of heat sink and cluster, it exhibits the contour nature of both the components. Almost 70% of base plate area is below 35°C, courtesy heat sink, surrounded by the central hot spot.[9],[10]

The forced ambient air at 20°C passes through the fins at very high velocity and removes the heat from the fins. This yields satisfactory result as the highest temperature spot is just about 37°C in a small area and remaining area having 30°C as an average temperature as shown in Figure 10.

As the solders are in immediate vicinity of the source, they are in direct contact with the source hence are having the same maximum temperature. The CFD analysis of the problem yields following results shown in Table 3.

| Parameter                | Temperature (For 1000W) | Temperature (For 100W) |
|--------------------------|-------------------------|------------------------|
| Source                   | 174.3 °C                | 43.408 °C              |
| Solder 1                 | 174.3 °C                | 41.029 °C              |
| Upper DBC                | 160.3 °C                | 38.651 °C              |
| Ceramic Substrate        | 155.9 °C                | 36.272 °C              |
| Lower DBC                | 136.5 °C                | 33.893 °C              |
| Solder 2                 | 132.9 °C                | 31.515 °C              |
| Base Plate of Heat Sink  | 120.7 °C                | 29.136 °C              |
| Heat Sink                | 88.3 °C                 | 26.757 °C              |
| Tip of Heat Sink         | 45.7 °C                 | 22 °C                  |

4.2. Experimental Results for 100W

Following Table- IV represent the temperature values taken from experimental setup for 100W

| Parameters               | Temperature (°C) |
|--------------------------|------------------|
|                          | IGBT with Heat Sink | IGBT with Heat Sink and Forced Air Cooling |
| Source                   | 43.2             | 42.8              |
| Solder 1                 | --               | --                |
| Upper DBC                | 40.1             | 39.7              |
| Ceramic Substrate        | --               | --                |
| Lower DBC                | 36.2             | 35.9              |
4.3. Comparative Result Discussion of Numerical and Experimental Method

The temperature obtained numerically was 43.408°C which was nearly equal to experimentally obtained temperature of 43.2°C. Also the temperature obtained with using heat sink with cooling was 42.8°C. Experimentally the results are taken for 100W and similar cooling can be done for 1000W in Hybrid Electrical Vehicle. The results can be formulated together in each layer as shown in Table 5.

| Parameter                  | Effect and result of optimization                                                                 |
|----------------------------|---------------------------------------------------------------------------------------------------|
| Solder 2                   | -                                                                                                |
| Base Plate of Heat Sink    | 34.6 33.9                                                                                        |
| Tip of Heat Sink           | 30.2 27.9                                                                                        |
| Ambient                    | 22 22                                                                                           |

4.4. Comparative Results formulated at various parameters

| Sr. No. | Parameter                | Effect and result of optimization                                                                 |
|---------|--------------------------|---------------------------------------------------------------------------------------------------|
| 1       | Substrate thickness      | The total thickness of substrate layer is 1.027 mm. It is so compact hence thermal resistance is low which increases the heat flow and helps to cool the IGBT. |
| 2       | Base plate               | Base plate thickness=5mm Pure copper is used as it has high thermal conductivity with reasonable heat resistance. It helps to spread the heat to the fins and lowers the temperature of the IGBT. |
| 3       | Thermal conductivity     | The materials used are having maximum possible thermal conductivities which increase the heat flow. |
| 4       | Type of flow             | Parallel forced air cooling is utilised to give maximum possible heat removal rate.               |

5. Conclusion

The total thickness of substrate layer is 1.027 mm. It is so compact hence thermal resistance is low which increases the heat flow and helps to cool the IGBT. Pure copper is used as it has high thermal conductivity with reasonable heat resistance. It helps to spread the heat to the fins and lowers the temperature of the IGBT. The materials used are having maximum possible thermal conductivities which increase the heat flow. Parallel forced air cooling is utilised to give maximum possible heat removal rate. The extruded fins are used with a spacing of 1 mm which are much effective. They help in reduction of temperature from 43.2°C to 27.9°C. Further an experimentation was done on a IGBT using an Inverter circuit. The results obtained at ambient temperature that is 22°C at different conditions. The conditions were without cooling effect, with Natural cooling effect and then by using Forced cooling effect. Also it was analyzed on ANSYS software and it was observed that the results obtained numerically and experimentally were nearly the same.

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