

# Power Electronics Component Location and Heat Sink Length Optimization – Hybrid Electrical Vehicle (HEV)

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## Abstract

**Background/Objectives:** Main components of Electric Vehicle (EV) inverter such as Insulated Gate Bipolar Transistors (IGBTs) and diodes are sensitive to temperature and must operate below fixed temperature limits to function effectively. Currently there are high demands in reducing the size of the inverter to fit in limited space available in vehicles and also to increase the output. **Methods/Statistical Analysis:** This paper focuses on optimizing best location of Power Electronic (PE) components with heatsink and optimizing the length of heatsink in order to reduce the overall temperature of a Hybrid Electrical Vehicle (HEV) inverter. The heat transfer model of IGBTs and diodes was modelled in MATLAB environment. The model was enhanced to incorporate heat sink model which was developed based on commercially available heatsink. Simulated annealing optimization method was used for both the optimization. **Findings:** Applying component location and heatsink length optimization, initial maximum temperature of inverter is reduced from 131.616°C to 126.979°C. Further, total heat sink length was also reduced from 48cm to 32.1cm. The results obtained clearly indicate that this method is successful as it is able to reduce the overall temperature by 5°C. It is indeed a new finding as current research on heat sink only focuses on finding better heatsink material, interface material, better coolant type and fin optimization. **Application/Improvements:** Applying these optimizations in designing stage of an inverter can manage overall heat distribution in an inverter and shrink the packaging size which will lead to cost reduction in manufacturing.

**Keywords:** Hybrid Electrical Vehicle (HEV), Heat Sink Length Optimization, Inverter, MATLAB, Power Electronic, Placement Optimization

## 1. Introduction

Manufacturing of Electric Vehicle (EV) has increased over the decade as there is increasing awareness to reduce the carbon dioxide (CO<sub>2</sub>) emission reduction to the environment and as a substitute for fossil fuels. Electric vehicles (EV) are mainly made of electric motors, generators, inverters and batteries<sup>1</sup>. Inverters and converters contribute to 24% of the cost of an EV system<sup>2</sup>.

Inverter plays a major role in EV system where it converts Direct-Current (DC) power from the batteries into Alternating-Current (AC) power for electric motors. Insulated Gate Bipolar Transistors (IGBTs) and diodes in Hybrid Electric Vehicle (HEV) inverter are sensitive to

temperature and must operate below 125°C to function efficiently<sup>1</sup>. High output and high performance of power electronic components requires a better thermal management<sup>3,4</sup>. Heat sink plays a vital role in reducing temperature of Power Electronic (PE) components by direct cooling method where it acts as a medium to absorb heat from the PE and dissipate it to the surrounding.

Various techniques such as reducing thermal resistance in Thermal Interface Material (TIM)<sup>5</sup>, double side cooling for power electronics<sup>6</sup>, optimizing pin fin of heat sink<sup>7</sup>, and package design concept<sup>1</sup> are being analysed to improve the transfer rate of the heat sink. Attention is also given to reduce the cost, volume and weight of an inverter while maintaining the reliability<sup>1</sup>. Minimal research is

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done on thermal behaviour of component placement optimization and heat sink length optimization methods.

This paper focuses on thermal behaviour of component placement optimization and heat sink length optimization of PE components in HEV inverter. The modelling of heat transfer model of heatsink with PE components is described in Section 2. Later, the component location and heatsink length is optimized using Simulated Annealing process in Section 3. Simulation results from modelling and optimization were discussed in Section 4. This paper is concluded in the subsequent section.

## 2. HEV Inverter Component Modelling with Heat Sink

### 2.1 Heat Transfer Modelling for HEV Inverter Components

For this project, power semiconductor layout of Toyota Prius 2004 model<sup>5</sup> is used as shown in Figure 1(a). This inverter drives 2 electric machines namely traction motor and generator. This study focuses on the inverter part which drives a traction motor highlighted in yellow dashed line as shown in Figure 1(a). This inverter have a total of 24 PE component which consists of 12 IGBT and 12 diode pairs like in Figure 1(b). This heat transfer model<sup>8</sup> was modelled in MATLAB environment<sup>11</sup> and modified according to HEV requirement with heatsink for each PE component.

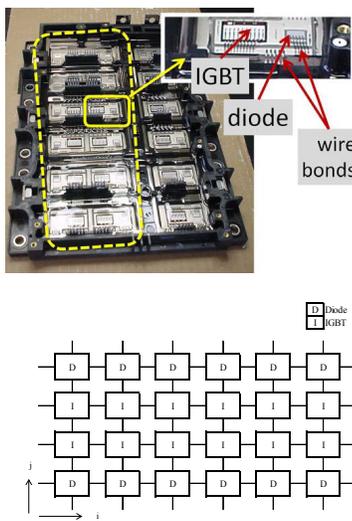


Figure 1. (a) HEV Inverter MY2004 Prius<sup>7</sup>, (b) Representation of Toyota Prius Inverter.

Junction temperature at each node  $(i, j)$  at current time is calculated using discrete heat equation as in equation (1). This heat balance equation includes boundary temperatures at the edge of the inverter, ambient temperature, junction temperature at each node and junction temperature from neighbouring component which interacts to neighbouring components via heat exchange and heat conduction shown in Figure 2. Schematic representation of heat balance at node  $(i, j)$  is shown in Figure 3. Boundary temperature  $T_{ij}^b$  and initial temperature  $T_a$  are as equations (2) and (3) which are assumed to be at 105°C because of harsh surrounding temperature in inverter.

$$T_{ij}^{m+1} = (1 - hc_{ij} - hR_{ij})T_{ij}^m + h[a_{ij}T_{i-1,j}^m + a_{i+1,j}T_{i+1,j}^m + b_{ij}T_{i,j-1}^m + b_{i,j+1}T_{i,j+1}^m] + hP_{ij} + hR_{ij}U_{ij}^m \quad (1)$$

$$T_{ij}^0 = T_{ij}^*, i = 1, I ; j = 1, J \quad (2)$$

$$T_{ij}^m = T_{ij}^b, i = 1, I ; j = 1, J \quad (3)$$

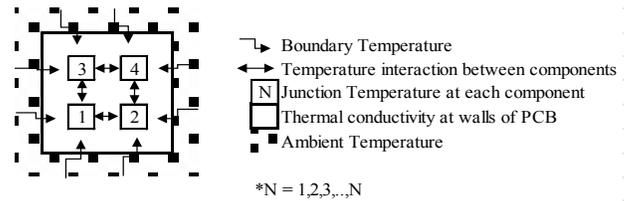


Figure 2. Block diagram of PCB with components and its thermal interaction.

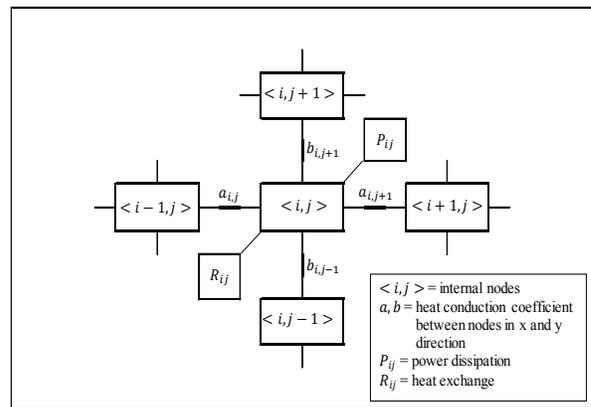


Figure 3. Schematic representation of heat balance at node  $(i, j)$ .

These IGBTs and diodes in inverter are represented by  $I \times J$  internal nodes while  $i=0$  &  $i=I+1$  or  $j=0$  &  $j=I+1$  are

**Table 1.** Variable values and details for equation (1)

Name	Variable	Value	Location
Heat conduction coefficient between nodes	$b_1, b_2, b_3, b_4, b_5, b_6$	$20 / 262 [sec^{-1}]$	Components at bottom wall with $T_b$
	$a_1, a_7, a_{13}, a_{19}$	$20 / 262 [sec^{-1}]$	Components at left wall
	$a_6, a_{12}, a_{18}, a_{24}$	$20 / 262 [sec^{-1}]$	Components at right wall
	$b_{25}, b_{26}, b_{27}, b_{28}, b_{29}, b_{30}$	$sec^{-1}$	Components at top wall which is insulated
	$a_k, b_k$	$18 / 262 [sec^{-1}]$	Otherwise
Heat exchange coefficient $R_{ij} = r_k$	$r_k$	Heat sink length equation in datasheet	All 24 components
Power dissipation $P_{ij} = P_k$	Diodes	$Q1 = 9.56 / 2.62 [^{\circ}C / sec]$	Diodes
	IGBTs	$Q2 = 38.24 / 2.62 [^{\circ}C / sec]$	IGBTs

the boundary nodes. Time marching process is used to find temperature at each node<sup>8</sup>. The values assigned to  $a_{ij}, b_{ij}, R_{ij}, P_{ij}$ , and  $\gamma$  are constant throughout the time marching process. Variable used in equation (1) is described in Table 1. The values are adopted from Steinberg<sup>9</sup> and edited according to HEV specification. The  $R_{ij}$  value for the table below will be explained in detail in section 2.2.

### 2.2 Heat sink in HEV Heat Transfer Model

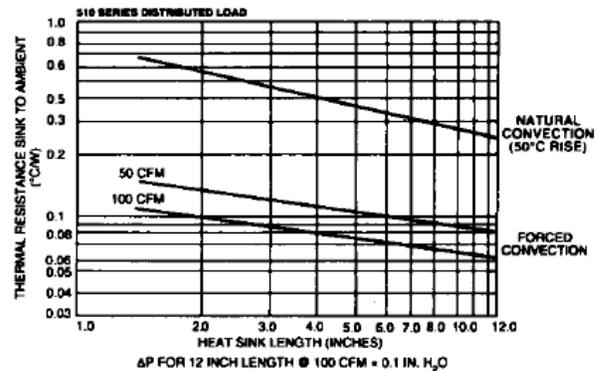
A commercially available heat sink which is suitable for power modules, IGBTs and Relays is selected for each component in this inverter. Natural convection data from Thermal Resistant versus Heat Sink Length graph shown in Figure 4 is used from datasheet<sup>10</sup> to determine thermal resistance equation. Figure 5 shows a manually plotted Thermal Resistance versus heatsink length graph using data obtained earlier. Then a linear line is plotted to get thermal resistance equation as in equation (4).  $R_{sa}$  value from equation (4) is included into equation (1) as Heat exchange coefficient value,  $R_{ij}$ .

$$R_{sa} = -0.0115length + 0.5952 \tag{4}$$

## 3. Component Placement and Length Optimization

The process of optimization is divided into 2 steps, which are:

- i. Component placement optimization was carried out with fixed length of heatsink (8cm)
- ii. Heat sink length optimization based on best placement location results obtained in (i)



**Figure 4.** The thermal resistant versus heat sink length graph.

### 3.1 Component Placement Optimization

Once the heat transfer model is developed according to Toyota Prius Inverter component location, the component placement is optimized by Simulated Annealing Method where the overall inverter heat is distributed uniformly in the inverter, reducing maximum junction temperature at each component. Component which is generating high temperature is identified from the heat transfer model. Then, random location was generated by custom data type method to locate these components. Simulated

annealing function will take initial maximum temperature and component locations as input and give a possible new location to reduce the maximum temperature. The process continues until the temperature difference is  $1 \times 10^{-12}$  with previous temperature, to give best location of components with reduced maximum temperature.

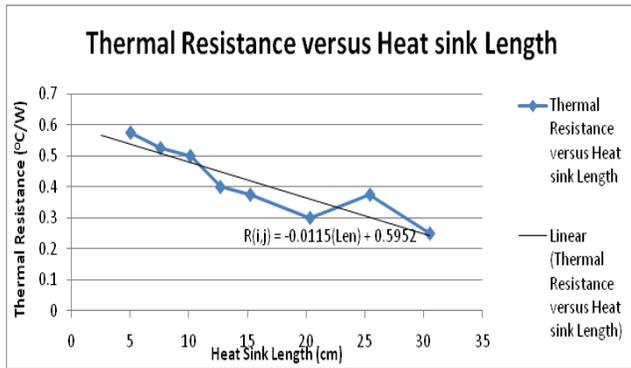


Figure 5. Manually plotted Thermal Resistant versus Heat Sink Length Graph.

### 3.2 Heat sink length Optimization

When optimum component location is found, the maximum temperature was further reduced by optimizing the heatsink length. At initial state, all components were set to have heat sink with 8cm length. Using equation (4) in the heat transfer model, heat sink length for each component is optimized using simulated annealing method. A minimum length of 3cm and maximum length of 8cm was set for this length optimization. Component location and length information for each component were generated using custom data type method. The optimized length will be in between 3cm and 8cm which give reduced length and maximum temperature of the overall inverter. Figure 6 explains the process in flow chart representation.

## 4. Simulation Results in MATLAB and Discussion

Temperature of the initial heat transfer model represented in Figure 1(b) is shown in Figure 7. The highest temperature for the first iteration is indicated as 131.616°C at IGBT area. From Table 2, it is observed that after component placement optimization, the maximum temperature of 131.616°C is reduced to 128.733°C. After length optimization, the maximum temperature is further reduced until 126.979°C. From both optimizations, the maxi-

imum temperature is reduced approximately 5°C. Figure 8 shows mesh grid representation of temperature at each component after placement and length optimization have taken place.

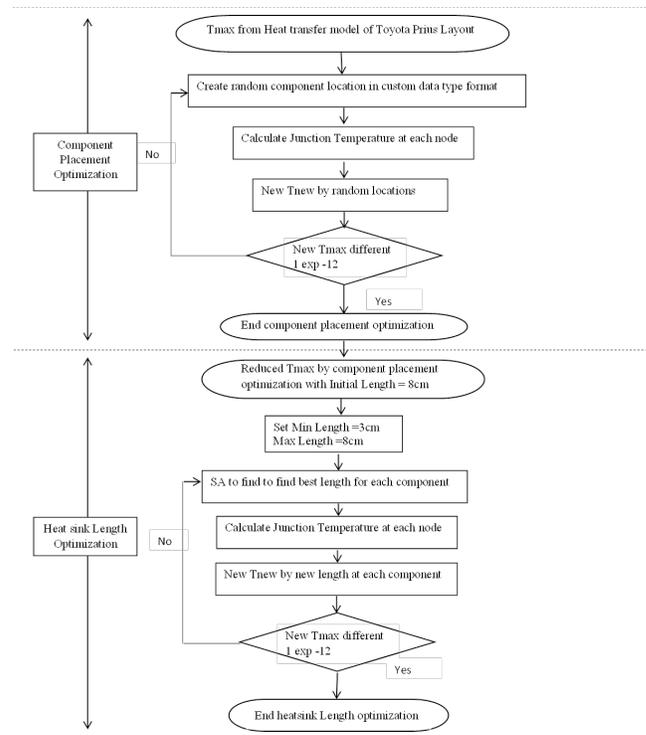


Figure 6. Simulated Annealing process in flow chart representation.

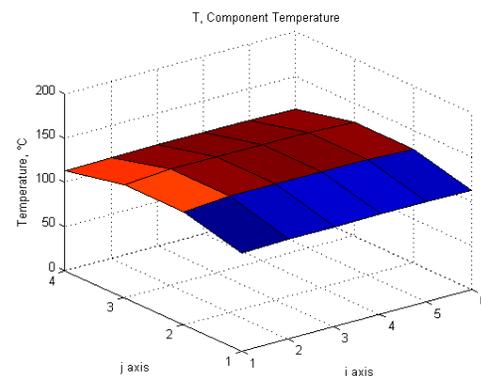
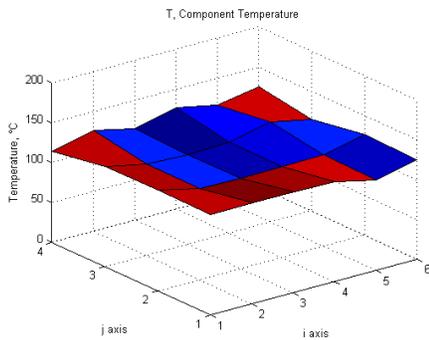


Figure 7. Mesgrid representation of temperature at each component before any optimization.

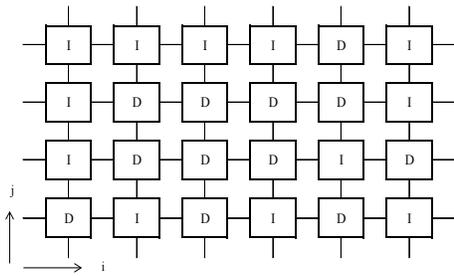
After the component placement optimization, the PE component location in inverter becomes as in Figure 9. Figure 10 shows each component's length after length optimization process has taken place.

**Table 2.** Maximum temperature at each iteration

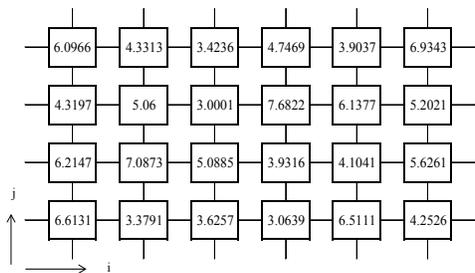
Iteration	Temperature (°C)	
	Component Placement Optimization	Heat sink Length Optimization
0	131.616	128.733
200	128.949	126.979
400	128.733	126.979
600	128.733	126.979
800	128.733	126.979
1000	128.733	126.979
1200	128.733	



**Figure 8.** Mesgrid representation of temperature at each component after placement and length optimization.



**Figure 9.** Optimized component location in HEV inverter.



**Figure 10.** Optimized heat sink length of each component.

## 5. Conclusion

Component placement and heatsink length optimization have been computed by MATLAB for heat transfer model of Toyota Prius Inverter. Maximum temperature of heat transfer model was successfully reduced at the end of both optimization processes.

By optimizing component location and heat sink length, overall maximum temperature of the inverter was reduced about 5°C from 131.616°C to 126.979 °C. Heat sink length optimization on the other hand, reduces total heat sink length from 48cm to a maximum total length of 32.1cm.

This shows that optimizing component location and heatsink length method is improving overall heat distribution in the inverter. While keeping the component cool, this passive cooling method is also reducing the length of heat sink. Applying this method in designing stage of an inverter can shrink the packaging size which will lead to cost reduction in manufacturing.

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