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Heatsink design using iterative calculation and thermal simulation for three-phase inverter

***Abstract**. The design of the power electronics system requires a crucial step – power loss estimation. When losses are estimated by the simulation approach it can significantly reduce the design time of the device cooling solution. This paper presents an estimation of power losses in three phase-inverter in different operation points, to determine the worst-case scenario. For this simulation, MATLAB Simulink is used, and simulation results in the form of the losses are used in another software to visualize thermal spreading at the heatsink.*

***Streszczenie.** W projektowaniu urządzeń energoelektronicznych dużą rolę odgrywa ocena strat mocy skutkujących wydzielaniem ciepła. Artykuł prezentuje ocenę strat mocy w trójfazowym przekształtniku. Określono rozpraszanie się ciepła w tym urządzeniu. (**Ocena rozpraszania w trójfazowym przekształtniku**) ciepła*

Keywords: Inverter, thermal distribution, power losses, MATLAB.
Słowa kluczowe: rozpraszanie ciepła, straty mocy, przekształtnik.

Introduction

Nowadays, the field of power electronics is experiencing an innovation boom, which leads to volume minimization and increasing power densities. The result is the generation of much higher heat flux at the level of the semiconductors. Because in power electronics, reliability and lifetime is a very important aspect. Therefore, the temperatures of the semiconductors cannot be exceeded to ensure this criterion. So, the estimation of the power losses is a very important step in the design of the device. [1], [2], [3]. The designer has many options to choose from. For example, direct calculation with the usage of the RMS and AV values of the current and voltage of the component [4]. The next approach is using a static or dynamic model of the components. This leads to accurate loss estimation, but accuracy heavily depends on model accuracy. If the model must represent components very accurately, this increases its complexity and, thus, estimation time [5]. The next approach is using a finite element method to estimate temperature and flux, too [6], [7], [8]. At least, the experimental estimation can be used too, but this requires a physical sample of the device [9], [10], [11].

Many publications use only static parameters to estimate power losses in the device [12], [13]. When dynamic parameters are used, they are used only at one temperature and one value of the current.

This paper is using the instantaneous voltage at the component to estimate conduction losses. For the switching losses estimation, instantaneous values of the turn on and turn off energies are used. All these values are temperature-dependent, so their values are changing with device temperature. For thermal analysis, the thermal model is created. This model uses values of the thermal resistances of the heatsink and transistor to calculate the temperature at various points. Finally, these two models are interconnected. The thermal model is using values of power losses calculated by the loss model to estimate temperature. The calculated temperature of the junction is fed back to the loss model. The model can use actual temperature to scale voltages and energies because they are temperature-dependent.

The value of the average power losses from the MATLAB Simulink is used in the next program Fusion 360, which can visualize thermal spreading at the heatsink to better design the cooling solution. Losses in this paper are calculated in the three-phase inverter with IGBT semiconductors. The load is represented by the induction motor with a power of 7500 W.

The presented model in this paper can be used in different topologies of the converters and can be used with different IGBT semiconductors.

Loss estimation

The electro-thermal model in the MATLAB-Simulink was created to estimate power losses in the three-phase inverter. This model consists of the FOC block for proper inverter controlling. The load is represented by the induction motor. Finally, the inverter is composed of IGBT semiconductors. For loss calculation, characteristics of the used devices were inserted in this IGBT model from the manufacturer datasheet. Characteristics are inserted separately for the IGBT switch and the internal diode of the IGBT. For the diode losses calculation, characteristic $I_f=f(U_f, T)$ was used. For diode switching losses, reverse recovery energy was used too. To calculate losses in the IGBT, the characteristic $I_c=f(U_{ce}, T)$ was used. For switching losses, turn on and turn off energy characteristics were used as a function of the current and temperature, E_{ON}, $E_{OFF}=f(I_c, T)$. All characteristics are implemented at two temperatures, 25°C and 175°C. The values of voltages and energies at other temperatures are recalculated using approximation. In Fig. 1, the implemented characteristics of used IGBT from ON Semiconductor company FGY40T120SMD are shown.

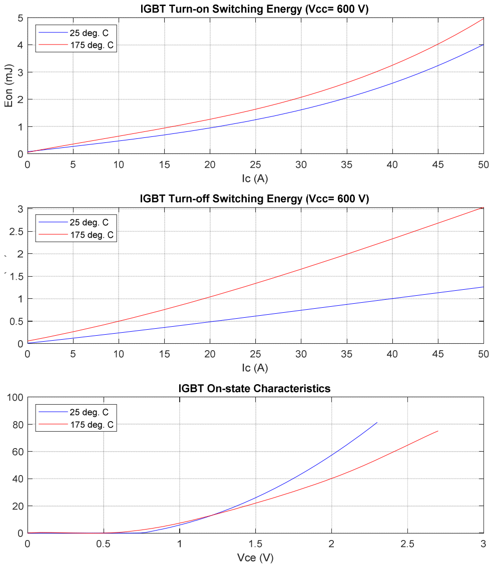

Fig.1. IGBT characteristics in MATLAB Simulink model

Because the thermal resistance of the heatsink is not yet known, the dependency of the inverter losses versus the temperature of the semiconductor was investigated first. The simulation was created at two speeds, 1440RPM and 500RPM and constant load torque 50Nm. Heatsink thermal resistance was changing from 1°C.W^{-1} to 0.3°C.W^{-1} with 0.1°C.W^{-1} steps. In total, 16 simulations were performed to simulate dependency of the losses at temperature. The results can be seen in Fig.2.

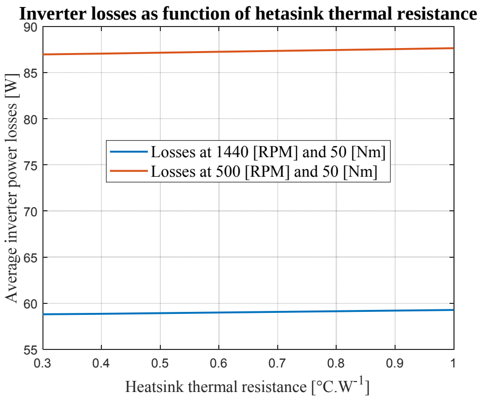

Fig.2. The result from the simulation of power losses

Results clearly show that the change of power losses is very small when changing the thermal resistance of the heatsink. As can be seen in Fig.1, change in voltage and energies is small when considering semiconductor current 19A. When the value of power losses is known, we can calculate used heatsink thermal resistance based on this data.

For this, the iteration method was used [14]. This method used heatsink dimensions and the known value of the power losses to estimate heatsink thermal resistance and convection heat transfer coefficient, which will be used later. This method is calculating parameters at no airflow, considering only convection heat transfer.

First, the temperature of the heatsink is estimated. Then according to the physical dimensions of the heatsink, dynamic, and kinematic viscosity of the cooling medium, in this case, air, the Nusselt number is calculated. From this number, thermal resistance and the convection coefficient can be calculated. In total, ten iterations were made to accurately estimate the heatsink thermal resistance and temperature. For the power losses value of 87.5 W was used. Dimensions of the heatsink were 300x165mm with a rib height of 30mm and the number of ribs 14. The results from the iterative method can be seen in Fig.3 and Fig. 4.

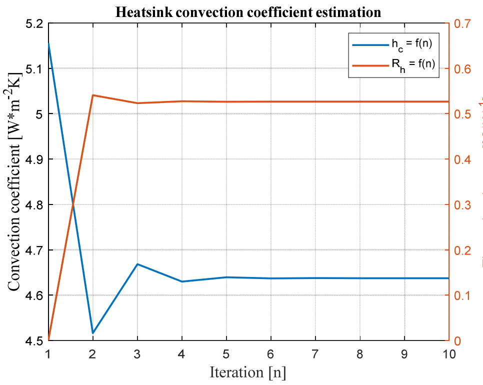

Fig.3. Results from the iteration method

As can be seen, the thermal resistance of the heatsink is about 0.52 °C. W^{-1} and convection coefficient of the used heatsink is 5.02 W.m^{-2}. K. This value of the convection will be used later in the visualization of the heat spreading in the 3D model of the heatsink.

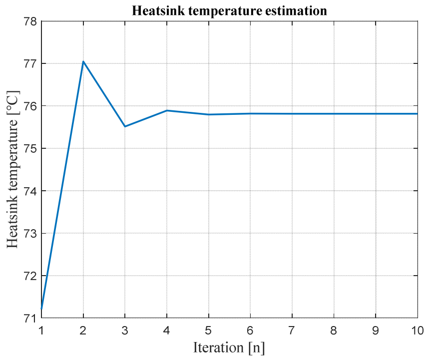

Fig.4. The temperature of the heatsink from the iteration method

The steady-state temperature of the heatsink is about 75.8°C. Now the value of the thermal resistance of the heatsink is known, we can use this value as input to the MATLAB parametric simulation.

The application of the inverter and motor is representing a simulator of an electric vehicle on a power scale 1:10. The motor can run at different speeds and loads during operation. Because of that, losses must be investigated at this operation points to determine the worst-case scenario of the inverter when power losses are the highest. For this, the parametric simulation was created with five different values of the speed and torque. In total, 25 simulations were performed to gather all data. The gathered data from the simulation are steady-state inverter losses, the temperature of the heatsink, and the junction of the IGBT device and output power. According to this data, efficiency can also be calculated. In Fig. 5 inverter losses are shown as a function of torque at different speeds, which represent possible operation points of the vehicle.

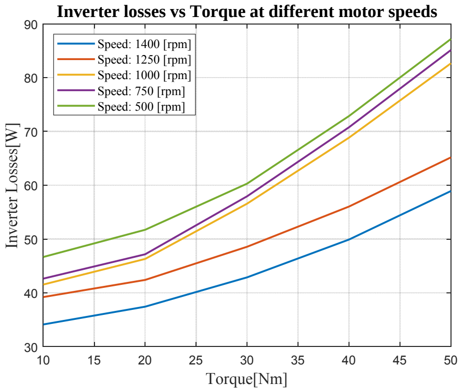

Fig.5. Power losses of the inverter from the MATLAB Simulink simulation

As expected, results from Fig.5 shows that power losses of the inverter are not highest at nominal speed and torque of the motor, but at the lowest speed and highest torque, because of high currents flow and low back EMF of the motor. Therefore, heatsink must be designed in a worst-case scenario, with an additional margin. In this case, the worst-case scenario loss is 87.5W.

In the thermal part of the simulation, the junction to case thermal resistance R_{jc} was used from the datasheet. The case to heatsink thermal resistance R_{ch} was represented by the value of the 0.4°C/W. This value was derived from the datasheet of the used thermal insulating pad. The thermal resistance of the heatsink was calculated from the heatsink physical parameters and dimensions using an iterative method, as can be seen in Fig.3.

Now, when the thermal model is completed, results from the thermal simulation can be seen in Fig.6.

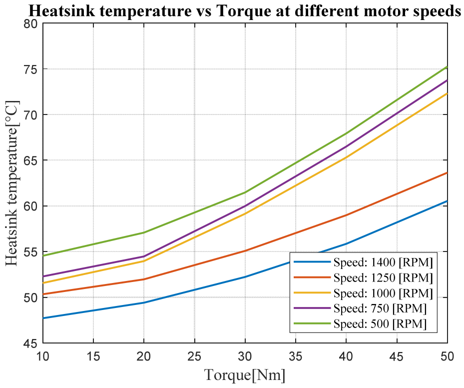

Fig.6. The temperature in the various points in the system

Finally, from the simulated data, the efficiency of the inverter can be calculated, too, as shown in Fig.7.

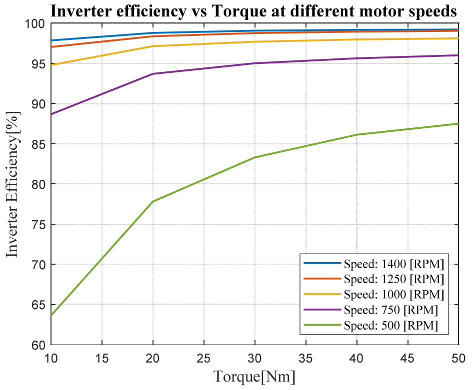

Fig.7. Inverter efficiency at different operation points

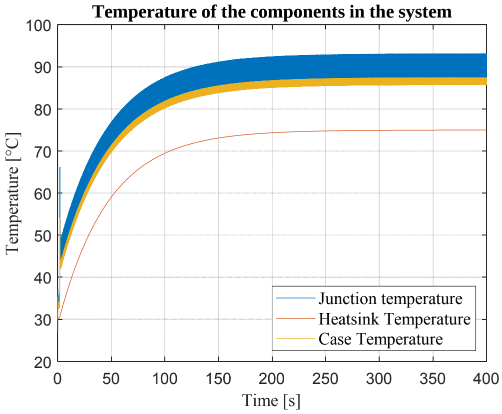

Fig.8. The temperature in the various points in the system

The efficiency of the inverter is lowest at the lowest speed and torque. Because of low inverter output power and quite high losses, efficiency at this operation point is about 64%. The highest efficiency of the inverter is at full speed 1400 RPM and full load 50 Nm when inverter outputs about 7400W. Efficiency is about 99.2 % at this point in the operation. Figure 8 shows the full simulation cycle of the inverter, where temperatures of the various points in the system are shown, as well as the effect of the thermal capacitance of the heatsink. Ambient temperature for all simulation were set to 30°.

As can be seen from Fig, 4, and Fig. 8, the temperature of the heatsink is the same.

Heat distribution

For the heat spreading visualization, the program Fusion 360 with a thermal option was used. This feature can calculate and simulate heat spreading across a model of the system. First, the model of the heatsink was drawn. Next, the transistor model is created as a component of three parts; case, backplate, and junction. This leads to a better determination of the heat spreading across the component. All parts are then connected to one composed model of the designed system.

Next, materials need to be defined. The Fusion 360 built-in material library consists of all the materials and their physical specifications needed for the simulation. The heatsink was defined as the aluminum, the case of the IGBT as epoxy resin, junction, and backplate of the IGBT as the copper.

When materials are defined, the next step is the definition of the areas where the heat is generated and where it is dissipated. The junction of every IGBT component was set as a heat source with a value of 14.5 W, so total system power loss is around 87.5W, as simulated in Fig.2. Next, the heatsink body is set as an area where heat can be dissipated to the surrounding area. For this, the convection coefficient must be known, and for our system, this coefficient was calculated by the iterative method in Fig.3. When all this data is defined, simulation can be started. The results can be seen in Fig. 9. The orientation of the heatsink in the preview has no effect on the calculated temperatures. The simulation is using a convection parameter to simulate temperatures at the heatsink surface. The calculated average temperature from the simulation is 77°C, which is very close to the estimated value in the Fig.4 by the iteration method and Fig. 6 by the MATLAB Simulink thermal simulation.

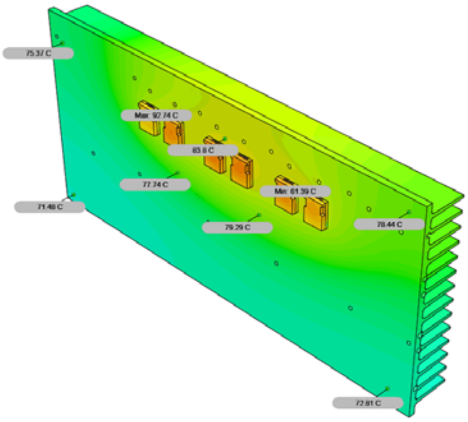

Fig.9. The result from Fusion 360 simulation – convection only

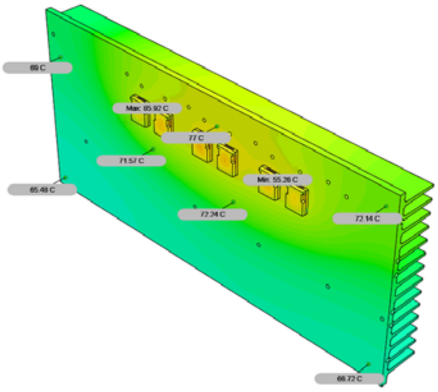

Fig.10. The result from Fusion 360 simulation – convection and radiation heat transfer

Fusion 360 is capable of taking to account radiation heat transfer too. For this purpose, the areas must be defined with the appropriate radiation coefficient. For the heatsink, the coefficient was chosen to be 0.08 because of the shiny material. The next part which can radiate heat is the IGBT semiconductor case. This case is made of epoxy resin what is, in most cases, a black material. Because of that radiation coefficient was chosen to be 0.98. Now when a new type of the heat transfer is defined, simulation can be run again to obtain new results shown in Fig. 10.

The average temperature in the new simulation considering radiation heat transfer is 70.6°C.

Conclusion

This paper discusses IGBT power loss estimation by simulation approach using the MATLAB Simulink software. The simulation uses the model of the transistor and its specifications provided by the manufacturer to estimate power losses in the inverter. The main goal was to investigate losses at different operation points of the inverter, because of its usage in the electric car. Because the thermal resistance of the heatsink was not known at the beginning, the parametric simulation was performed to investigate the dependency of the power losses and the heatsink thermal resistance. As can be seen in Fig.2, change in the power losses are minimal, and power losses can be considered as nearly constant. When the power losses are known, iterative estimation of the real heatsink based on the known power losses can be performed. The results are shown in Fig.3. The simulated value of the thermal resistance is 0.52 °C.W^{-1}. This value was used for MATLAB simulation. The power losses, temperatures, and efficiency were simulated, as can be seen in Fig.5, Fig.6, and Fig.7, respectively. From Fig. 5 worst-case can be observed at speed 500 RPM and torque 50Nm. From Fig. 7 the worst efficiency occurs at a speed of 500 RPM and torque of 10 Nm because of low inverter power output and quite high losses about 47W, as can be seen in Fig.5.

For the heat spreading simulation, Fusion 360 was used where the model of the heatsink and IGBTs was modelled and used. The value of the convection coefficient to this simulation was used from the iteration method calculated in Fig.3. First, only convection heat transfer was simulated, where the final average heatsink temperature was 77°C, which is nearly the same as the results in Fig. 4 and Fig. 8. The second simulation in the Fusion was performed with convection and radiation type of heat transfer. With these types of heat transfers, the average temperature at the heatsink surface dropped to 70.6°C. Since radiation was also used, this is a result of more in line with reality.

This proposed method is a very fast approach to get a semiconductor loss in the simulated system. Another advantage of this approach is the capability of simulating any topology of the converter because the model can be reconfigured to the desired one.

With this method, different transistors can be simulated, too, because the model accepts basic parameters that every manufacturer offers in the datasheet. Therefore, many types of transistors can be simulated in the desired topology, and the best one can be chosen based on the price and target efficiency of the system.

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