MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

THERMAL MODELLING, ANALYSIS AND DESIGN OF AN INTEGRATED MODULAR MOTOR DRIVE APPLICATION

Bekir Caner YAĞCI

E:caneryagci1@gmail.com

P: +90 535 977 5608

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1. Introduction

The aim of the project is to obtain a thermal model of an integrated modular motor drive having different heat sources such as; power semiconductors, integrated circuits, capacitors, motor windings etc., and analyse the thermal behaviour of individual parts. A natural cooled heatsink is developed for the system. FEA and Steady-State Lumped Parameter analysis are implemented on SolidWorks and MATLAB/Simulink whether the designed heatsink reach the criteria.

In this report, theoretical and practical knowledge about the project is shared. Firstly, basic heat transfer mechanism, the ways of thermal analysis, and thermal resistance calculation is explained. Then, implemented analysis, their results, and practical challenges that encountered during analysis are discussed. Finally, supplementary links and articles are given in the references part.

2. Heat Transfer Mechanism & Thermal Analysis Methods

There are three mechanisms of heat transfer. These mechanisms are:

1. Conduction

- Conduction is responsible for heat transfer inside a solid body (or solid body to solid body assuming 100% conduction between).

$$Q_{COND} = kA(T_{HOT} - T_{COLD})/L$$

Where:

Q_{COND} – Heat transferred by conduction [W]

k – Thermal conductivity [W/m/K]

A – Cross sectional area [m^2]

T_{HOT} – Temperature on the hot side [K]

T_{COLD} – Temperature on the cold side [K]

L – Distance of heat travel [m]

2. Convection

- Convective heat transfer is the heat flow between a solid body and the surrounding fluid (either liquid or gas).

$$Q_{CONV} = hA(T_S - T_F)$$

Where:

Q_{CONV} – Heat transferred by convection [W]

h – Convection coefficient [W/m^2/K]

A – Surface area [m^2]

T_S – Surface temperature [K]

T_F - Fluid bulk temperature [K]

- It can be either natural or forced convection.

- The magnitude of the convection coefficient strongly depends on the medium (fluid) surrounding a solid body.

Medium	Convection coefficient W/m^2/K
Air (natural convection)	5-25
Air/superheated steam	20-300
Oil (forced convection)	60-1800
Water (forced convection)	300-6000
Water (boiling)	3000-60000
Steam (condensing)	6000-120000

Figure 1: Convection coefficients for different media

3. **Radiation**
   - Radiation heat transfer occurs between a solid body and the ambient or between two solid bodies without presence of any medium (fluid).
   - Radiation is usually ignored since it has less effect than conduction, convection, and difficult to estimate.

$$q = \sigma T_s^4$$

Where:

q – Heat flux (heat emitted by radiation per unit of area) [W/m^2]

σ – Stefan-Boltzmann constant = 5.67x10^{-9} [W/m^2/K^4]

T_s – Surface temperature [K]

Also, there are three methods of thermal analysis. These methods are:

1. **Steady-State Lumped Parameter**
   - It is the method of thermal equivalent circuit of the interior of the system. This is analogous to an electric circuit, in that heat is generated by "current sources" that is the power loss and temperature is analogous to voltage. The rate of generation of heat in a source is measured in Watts. The heat flow rate, which is also measured in Watts, is analogous to current. Resistance is measured in °C/W.
   - It is the most straightforward method.
   - Capacitive and the inductive effects in the system can be ignored to analyse the steady-state behaviour of the system. Thus, only a resistive circuitry could be analyse to see the worst case scenario of the system.
2. **Finite Element Analysis (FEA)**
   - Well recognized tool used in the analysis of heat transfer problems.

- However, FEA can only analyze solid bodies and, by necessity thermal analysis with FEA is limited to conductive heat transfer. The other two types of heat transfer: convection and radiation must by approximated by boundary conditions.
- Requires a simulation program. (SolidWorks)

3. **Computational Fluid Dynamics (CFD)**
   - Modeling all three mechanisms of heat transfer without arbitrary assumption requires a combined use of FEA and Computational Fluid Dynamics (CFD).
   - CFD is the most complex computation method.
   - Requires a simulation program. (SolidWorks Flow Simulation, ANSYS Fluid Dynamics, etc.)

Beside the lumped parameter method, the method to use depends on the heat transfer mechanisms that are taking place in the components that you are designing: conduction, convection, radiation or a combination of them. In addition, the level of accuracy you are willing to accept will also influence your decision.

The table below summarizes the method to use depending on the type of heat transfer mechanisms you are analyzing:

Table 1: The tool to use depending on the type of heat transfer mechanisms analysed

Heat Transfer mechanisms	FEA	CFD	Either	Notes
Conduction only	X			No need to simulate fluid flow
Conduction w/ Predictable Convection			X	Faster with FEA. Need to know convection coefficients
Conduction w/ Unpredictable Convection		X		
Conduction, Radiation w/ Predictable Convection		X		FEA not practical
Conduction, Radiation w/ Unpredictable Convection		X		

Thermal resistance calculation for heatsink

Fin geometry, fin length, number of fins, material (usually aluminium), cooling (natural or forced), heatsink geometry are effective on the thermal resistance of the heatsink.

For the calculation of the thermal resistance of the heatsink an online calculator at "https://www.myheatsinks.com/calculate/thermal-resistance-plate-fin/" is used to hardly estimate the thermal resistance of the heatsink selected. Also, the datasheets of the selected heatsinks are controlled if they meet the thermal resistance range calculated in the steady state analysis.

For the analytical calculation of the heatsink thermal resistance see reference [12].

3. Steady-State Lumped Parameter Analysis

To implement the steady-state analysis on Simulink environment thermal resistance values are selected from the Gan System's own application notes. For more information see reference [5].

Given conditions are shown below;

- 120 Thermal via (0.3mm diameter)
- 6 Layer PCB
- Rjc= 0.5 Ω
- Rcpb= 4.5Ω(1.6mm & 6 layer)
- R_{TIM} = 1.5 Ω

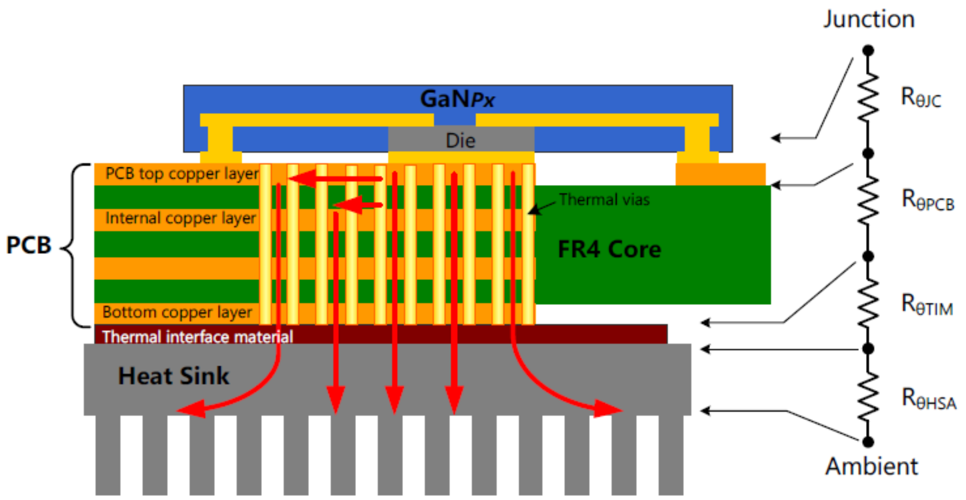

Figure 2: Bottom cooled GanFET connection

Figure 2 shows the lumped parameter circuitry of the bottom cooled GanFET. This circuit is drawn in Simulink environment as shown in the figure 3 with the given thermal resistance values. Then, voltage measurements are taken as temperature data from junction, case and heatsink. Ambient temperature is selected as 40 ℃. Finally, the Matlab code in appendix part is run to sweep the Rth(heatsink) parameter, and the results are plotted in figure 4.

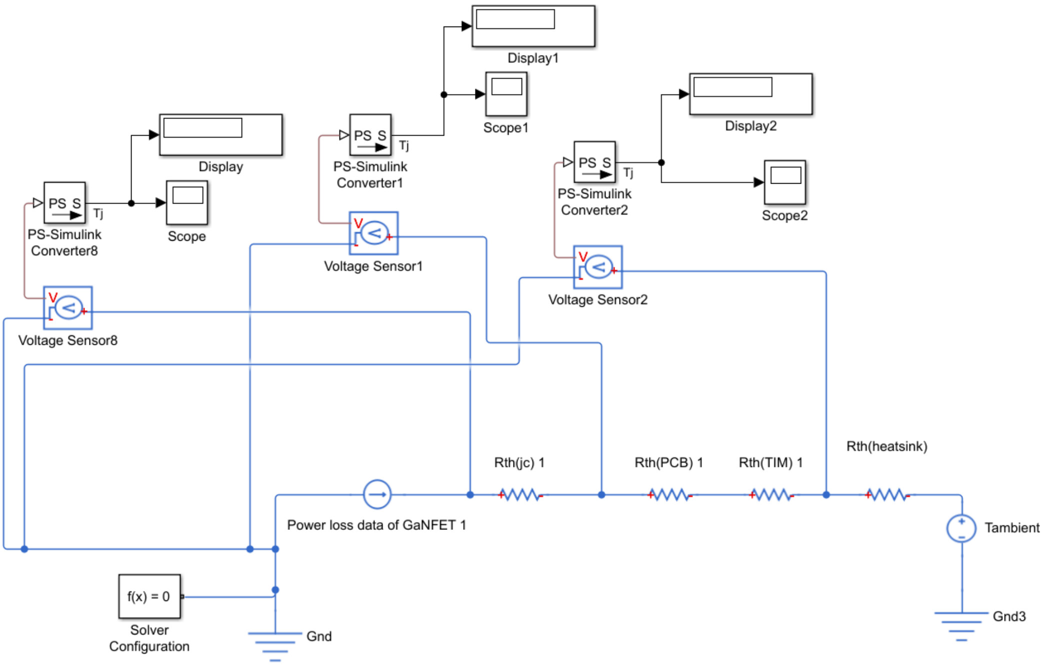

Figure 3: Steady-state Simulink model

The result of the analysis is shown in figure 4. According to the figure 4, junction temperature is 110 °C when the thermal resistance of the heatsink is 0.5°C/W. Thus, the thermal resistance of the selected heatsink must be less than or equal to 0.5°C/W approximately.

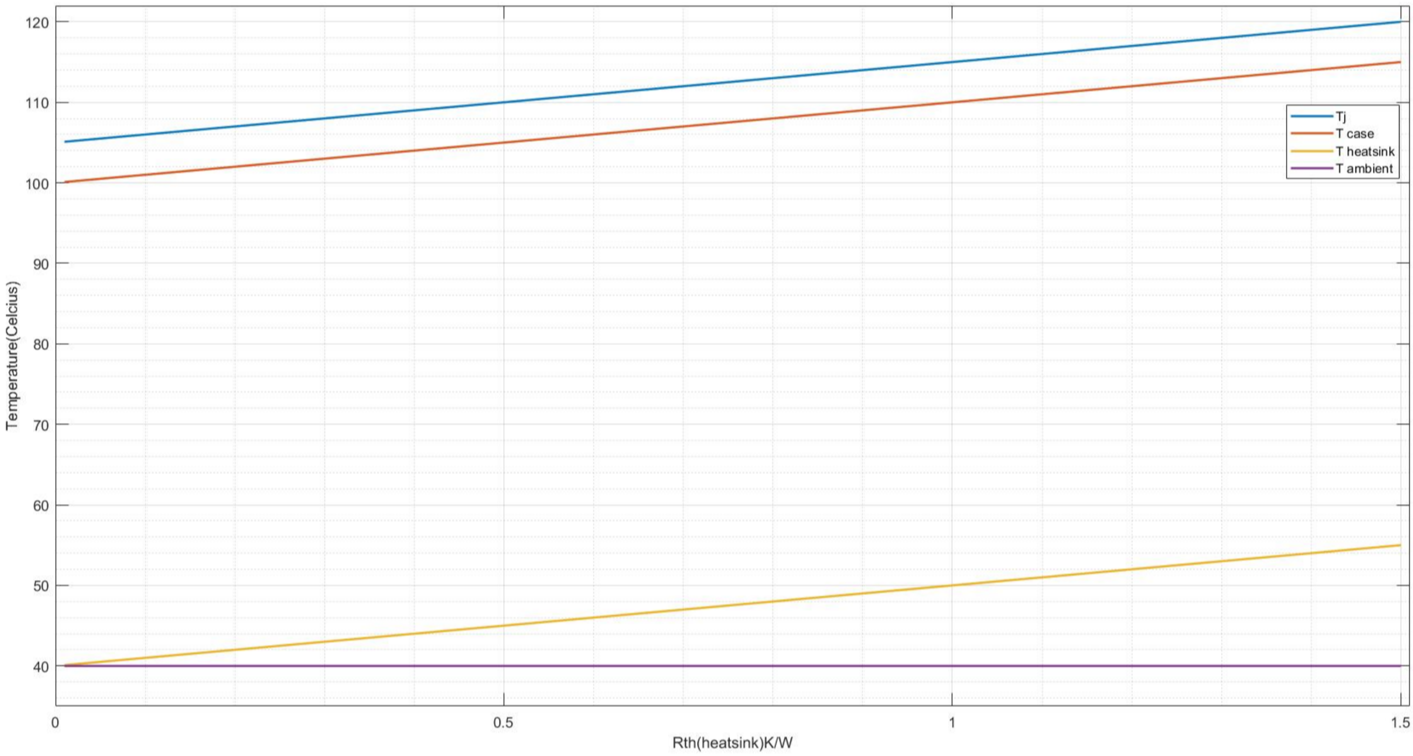

Figure 4: Temperature results

For the simulation files see reference [11].

4. FEA Analysis

FEA analysis is implemented on SolidWorks environment. For the implementation of the analysis a 3D CAD figure of a circular heatsink with 40mm fin length, 5 mm baseplate thickness, 150 cm radius is drawn. Holes for mounting and places for windings are cut. Aluminium alloy is selected as material. For the CAD Drawings and the thermal analysis results see reference [11]. To learn more about the SolidWorks thermal analysis see reference [3], [4]

With SOLIDWORKS Simulation which uses finite element method, only heat transfer by conduction is modeled directly. Convection and radiation are modeled as boundary conditions. This is done by defining convection and/or radiation coefficients. Thus, a convection coefficient between 5-25 °C/W must be defined to imitate natural cooling condition. Also, 6°C/W thermal resistance is defined via contact set to resemble the PCB and the TIM between each GanFET and the heatsink[4].

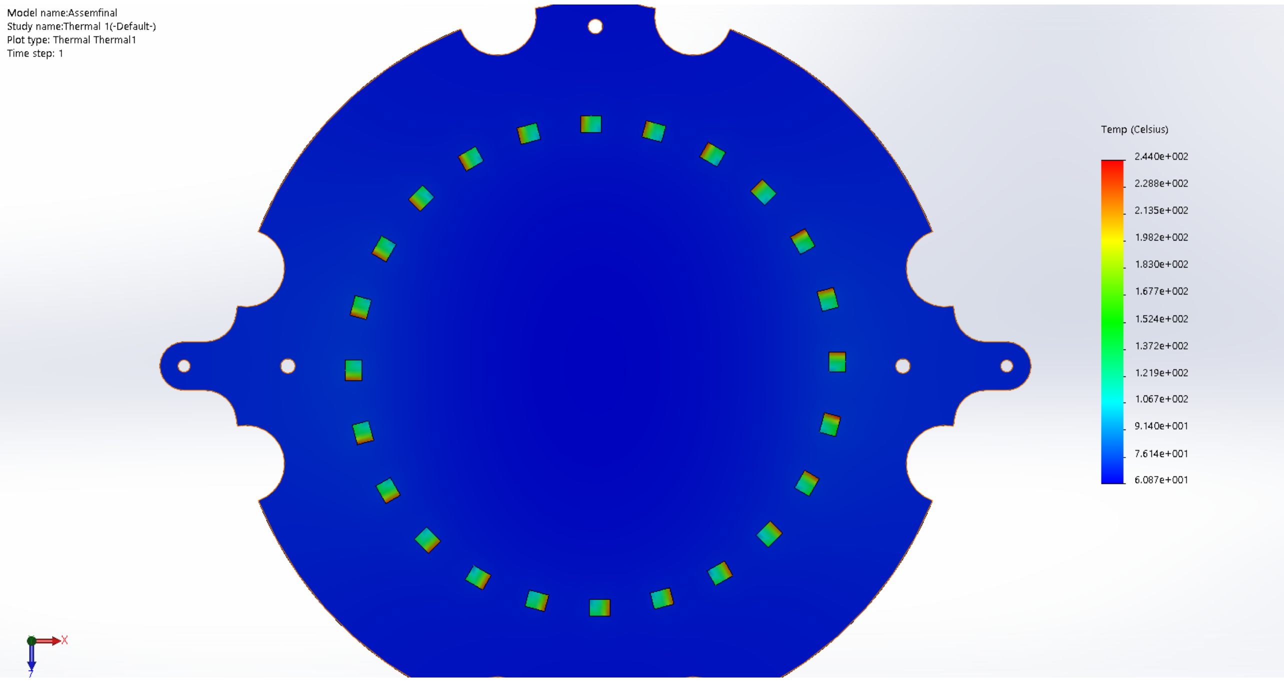

Figure 5: Overall heat dissipation on heatsink

The 3D drawing of the GanFET is available online or be see reference [11]. It can also be drawn with the given dimensions in the datasheet. For the thermal analysis only the thermal pad layer and the case is considered and the other layers such as drain, gate, soldering layers are ignored, since they increase the computation time and usually cause mesh errors.

GanFET is assumed to be a black box with a 0.5°C/W (create material with this specification) thermal resistance, and only conduction between the Gan's and the heatsink is from the thermal pad in the implemented analyze. Figure 6 shows the heat dissipaton on GanFET. Blue line in figure 6 is the thermal pad, and it shows that the conducted part of the GanFET is cooled and the operation is possible with this heatsink as long as the proper conduction between the heatsink and the GanFET is implemented. However if the conduction between the heatsink and the GanFET is not proper GanFET can be heated up to 244 °C.

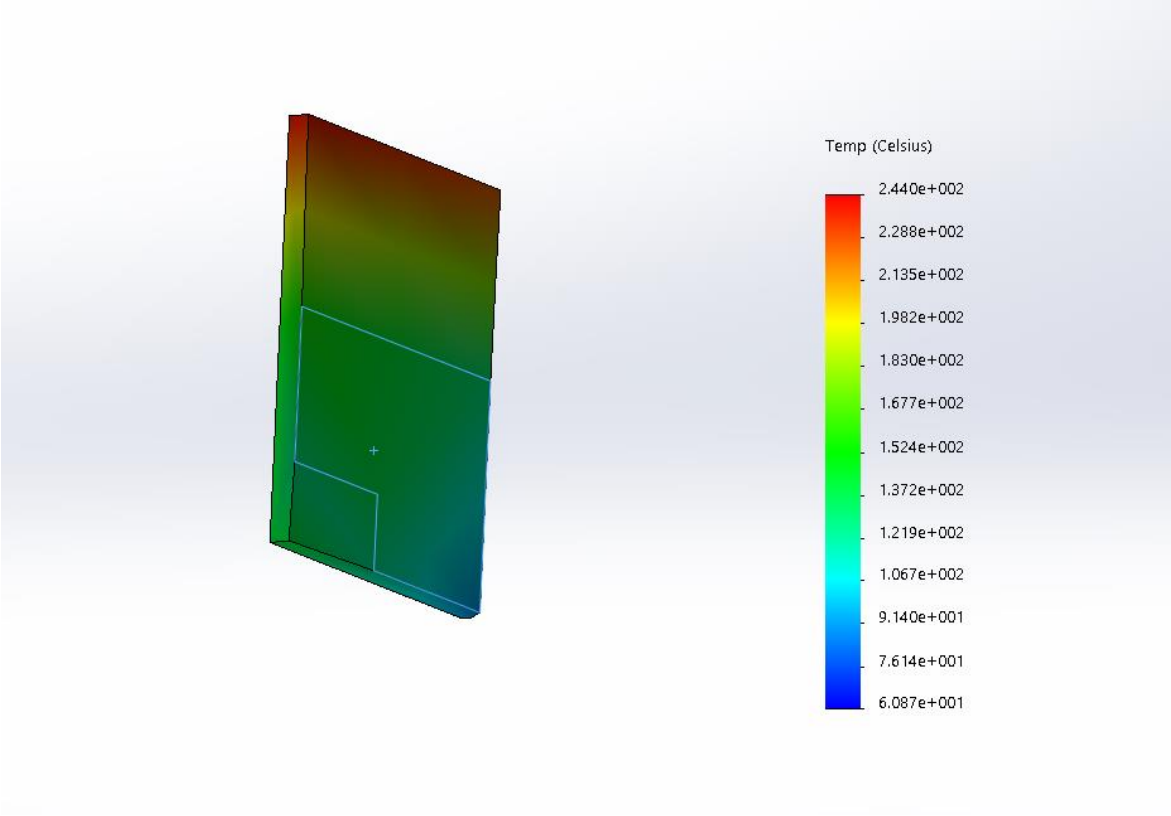

Figure 6: Heat dissipation on a single GanFET

Problems of FEA in SolidWorks

The problem is that the SolidWorks is designed for mechanical systems and it is not very easy to reach the most accurate solution if you draw the electronic components such as GanFET, PCB, etc. in SolidWorks, since it is a bit complicated. My advice is to design the 3D Drawings of the electronic components in another simulation program such as Altium, and combine mechanical parts and the electronic parts via import/export in SolidWorks/CircuitWorks.

5. References

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[3] http://blogs.solidworks.com/solidworksblog/2017/04/use-fea-vs-cfd-thermal-analysis.html

[4] https://www.youtube.com/watch?v=Z8ymNlJoitw&list=WL&t=0s&index=45

[5] https://gansystems.com/design-center/application-notes/

[6] https://kupdf.com/embed/miller-tje-speed39s-electric-motors_58b2bb6a6454a7ce1eb1eaad.html?sp=%7Bstart%7D

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[11] https://github.com/caneryagci/IMMD-Research

[12] Factor, P., & Perimeter, P. (n.d.). SIMPLIFIED METHOD FOR ESTIMATING HEAT SINK THERMAL RESISTANCE - Θ SA MATHEMATICAL FORMULA ANALYSES, 1–7.

Appendix: Steady-State Lumped Parameter Matlab Plot Code

```
Power_loss = 10;
Rth_jc = 0.5;
Rth_pcb = 4.5;
R_tim = 1.5;
T_ambient = 40;
ambient_t = ones(150,1)*40;
junc_temp = zeros(150,1);
case_temp = zeros(150,1);
heatsink_t = zeros (150,1);
resistance_h= zeros(150,1);

open_system('thermal_model');
for i= 1:1:150
  Rth_heatsink = 0.01*i;      %K/W
   sim('thermal_model');
   resistance_h(i) = Rth_heatsink;
   junc_temp(i)= Tj(51,2);
   case_temp(i) = T_case(51,2);
   heatsink_t (i) = T_heatsink(51,2);
end

plot(resistance_h,junc_temp,resistance_h,case_temp,resistance_h,heatsink_t,resistance_h,ambient_t,'LineWidth',1.5);
grid on;
grid minor;
legend('Tj','T case','T heatsink','T ambient','Location','northeast');
xlabel('Rth(heatsink)K/W');
ylabel('Temperature(Celcius)');
ylim([35 122]);
xlim([0 1.51]);
```