Parameter Calculations for SiC Three-Phase Rectifier

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***Abstract*—Main focus of this work is to design a three–phase rectifier based on silicon–carbide power diodes. Main part of the article is dedicated do equations which are then used to obtain temperatures of power diode junction based on current, voltage and switching frequency. From these, power losses are calculated. Combined with selection of cooling heat sink, final temperatures are obtained. There were two methods used. One simplified equation, neglecting shape of forward current to calculate forward losses and the second where the shape of current is acknowledged and calculated with. Final values are then reviewed via simulation.**

***Keywords*—rectifier, silicon, carbide, power, Schottky, diode**

I. Introduction

There has been a minor breakthrough in device power density and power losses since the silicon–carbide power components such as diodes, MOSFETs and other became commercially available. This is mostly due to high value of breakdown field, which is about ten times higher than in case of conventional silicon (Si) material. This allows much higher blocking voltage and low leakage current of power devices along with higher saturated drift velocity, allowing power devices to achieve much higher switching frequencies and higher thermal conductivity which lowers demands for heat management. As a result, smaller devices with higher output power can be designed. [1]

This article describes a design of a three-phase diode rectifier based on SiC diodes. Firstly, main components as the rectifying diodes and output capacitor are described followed by calculations of power losses and selecting a testing point for calculated values. These values are then tested in a PLECS simulation thermal model for validity with selected radiator. This project was assigned for needs of Department of Power Electronics and Machines for testing. It is assumed that the rectifier will be used in range of frequencies from 0 to 60 kHz.

II. Design of Three-Phase SiC Diode Rectifier

A. Rectifying components

As mentioned above, the aim is to design a high-power density rectifier based on SiC rectifying diodes. GeneSiC Semiconductor diodes were chosen for this task, specifically GB2X100MPS12-227. These diodes are promising in case of power density and low reverse current (I_R). Each diode module consists of two parallel SiC Schottky diodes. Maximal peak reverse voltage (V_{RRM}) is set to 1200 V per leg. Maximal forward current (I_{FM}) per leg is 182 A and maximum repetitive peak forward current (I_{FRM}) is rated at 600 A per leg. V_{RRM} and I_{FRM} are rated for case temperature of 25 °C and maximum I_{FM} value for 75 °C. [2]

In Fig. 1 typical forward characteristics of the diode are shown for temperatures from 25 to 175 °C. Considering forward current to be 182 A per leg, forward voltage would be around 3 V in worst case, which is considered to be the highest temperature of diode junction displayed in Fig. 1. [2]

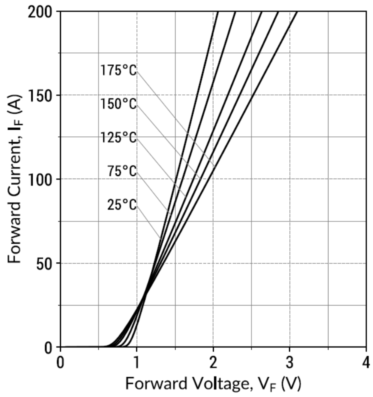

Fig. 1. Typical forward characteristics of GB2X100MPS12-227 [2]

Another important characteristics are shown in Fig. 2. The characteristics show dependence of total power dissipation (P_{TOT}) and case temperature (T_C). These characteristics give a raw idea of cooling demands and setting a test point. Every test point outcome must remain under the line displayed in the line in Fig. 2. [2]

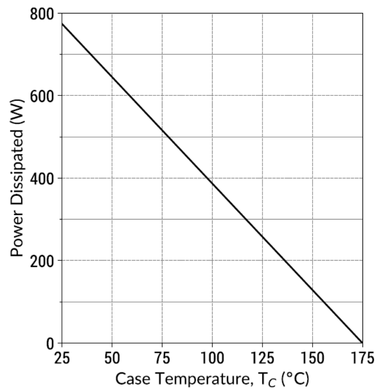

Fig. 2. Power derating curvers of GB2X100MPS12-227 [2]

B. Calculating power losses of diodes

Three values of reverse voltage (V_R) were chosen based on diode datasheet shown in Fig. 3. Because of limitation in form of maximal capacitor voltage, maximum of 900 V was selected. Another testing voltage value was set close to 0 V. As consequence, 20 V is the lowest testing value. The third value is 560 V. [2][4]

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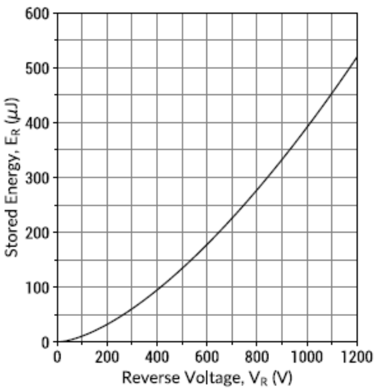

Fig. 3. Typical capacitive energy vs reverse voltage characteristics [2]

For forward losses (P_{FW}), we use following equations based on [2]:

$$P_{FW} = V_{BI}(T_j) * I_{AVG} + R_{DIFF}(T_j) * I_{RMS}^2 \quad (1)$$

I_{RMS} is a root mean square of the current flowing through the diode. I_F is diode forward current. The equation is as follows:

$$I_{RMS} = \frac{I_F}{\sqrt{2}} \quad (2)$$

I_{AVG} is an average value of the current flowing through the diode. Following equation was used:

$$I_{AVG} = I_F * \frac{2}{\pi} \quad (3)$$

V_{BI} is built-in voltage and it is function of junction temperature (T_j). It is calculated as:

$$V_{BI}(T_j) = -0.00123 * T_j + 0.995 \quad (4)$$

R_{DIFF} is differential resistance of the diode and also a function of junction temperature and equation is:

$$R_{DIFF}(T_j) = 1.19e - 07 * T_j^2 + 1.69e - 05 * * T_j + 0.00502 \quad (5)$$

During the first design were forward power loss equations simplified by selecting forward voltage (V_F) based on forward current from Fig. 1. This simplification is supposed to create power reserve for safe usage. Simplified equation is:

$$P_{FW}(I_F) = I_F * V_F \quad (6)$$

Tab. I represents four different values of forward voltage for four testing current values based on Fig 1. Forward current over 182 A was purposely selected for calculation values of junction temperature. [2][3][7]

TABLE I. FORWARD VOLTAGE VS FORWARD CURRENT

I_F [A]	50	150	170	200
V_F [V]	1.5	1.9	2.5	3.3

For calculation of switching losses, following equation is used from [3]:

$$P_{SW} = f_{SW} * E_R \quad (7)$$

Where f_{SW} is switching frequency of the rectifier and E_R is stored energy during the blocking phase of the switching cycle. Dependence of stored energy on reverse voltage is displayed in Fig. 3. Total power loss of diode is represented by [2][3]:

$$P_{TOT} = P_{FW} + P_{SW} \quad (8)$$

C. Selection of cooling aggregate

Flowing air has been selected as cooling medium mainly due to simple design of the device. To manage the heat of power components, aluminium heat sink by Fischer Elektronik was chosen. A full heat sink with two fans powered by 12 or 24 V is displayed in Fig. 4. [2][3][5]

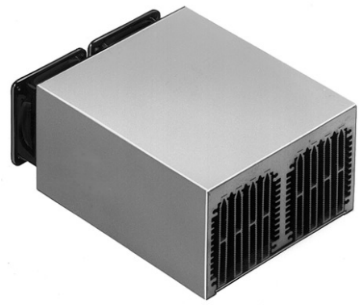

Fig. 4. Photo of aluminium heat sink from Fischer Elektronik [5]

Thermal resistance of junction to case can be found in diodes datasheet. It is valued at 0.19 K/W per leg. Another needed value is ambient temperature, which is set to be 30 °C. Thermal capacitances are neglected in calculations as they are assumed to be valued by value 1 J/K. [5]

With these values we now proceed in calculating temperatures of heat sink, case and junction in the same order. The equations are:

$$T_R(t) = T_A + R_{thra} * P_{TOT} * 1 - e^{\frac{-t}{\tau ra}} \quad (9)$$

Where T_R is temperature of heat sink as a function of time, R_{thra} is its thermal resistance and T_A is ambient temperature. [3][7]

$$T_C(t) = T_R(t) + R_{thcr} * P_{TOT} * 1 - e^{\frac{-t}{\tau cr}} \quad (10)$$

Where T_C is temperature of case and R_{thcr} is its thermal resistance. [3]

$$T_J(t) = T_A + P_{TOT} * (R_{thjc} * 1 - e^{\frac{-t}{\tau jc}} + + R_{thcr} * 1 - e^{\frac{-t}{\tau cr}} + R_{thra} * 1 - e^{\frac{-t}{\tau ra}}) \quad (11)$$

T_J stands for junction temperature of the diode and R_{thjc} junction to case thermal resistance. [3]

Tab. II serves as an example of temperatures of diode junction (T_J) gained by previous equations after approximately 10 hours of applied reverse voltage at 900 V. According to diode datasheet, temperature must not exceed 175 °C.

TABLE II. JUNCTION TEMPERATURE OF RECTIFIER DIODES

I_F [A]	50	150	170	200	f_{SW} [Hz]
T_J [°C]	45.50	76.50	82.70	92.00	**0.00**
	53.30	118.40	161.80	234.65	**500.00**
	54.29	119.39	162.79	235.64	**10^4**
	59.48	124.58	167.98	240.83	**$60*10^3$**
V_R[V]	**900 V**				

As shown above, red values symbolize exceeded junction temperature value, yellow values represent vaule which is close to absolute maximum rating of junction temperature. Temperature values within green color symbolize, that the rectifier is safe to use with these parameters.

After the first calculation using the simplified equation (6), the calculation was done again, this time using equation (1). Asuming that based on shape of diode current, which is basicaly half of a sine wave, the average current (I_{AVG}) is calculated according to (3). For I_{RMS}, equation (2) is used.

Values of diode junction temperature gained with this procedure are shown in Tab. III. It is clearly visible, that temperatures are noticably lower even in case of exceeding maximal forward current when using mentioned radiator.

TABLE III. JUNCTION TEMPERATURE OF RECTIFIER DIODES

I_F [A]	50	150	170	200	f_{SW} [Hz]
T_J [°C]	41.64	78.01	87.38	102.75	**0.00**
	41.69	78.06	87.43	102.80	**500.00**
	42.68	79.05	88.42	103.79	**10^4**
	47.87	84.24	93.61	108.98	**$60*10^3$**
V_R[V]	**900 V**				

In Tab. IV, temperatures of heat sink (T_R) are presented with maximum reverse voltage of 900 V. As shown, minimal temperature is 34.13 °C with forward current of 50 A. Maximal tempreture, on the other hand, is 56.18 °C.

TABLE IV. TEMPERATURES OF HEAT SINK

I_F [A]	50	150	170	200	f_{SW} [Hz]
T_R [°C]	34.13	47.04	50.36	55.81	**0.00**
	34.15	47.05	50.38	55.83	**500.00**
	34.50	47.40	50.73	56.18	**10^4**
	36.34	49.25	52.57	58.02	**$60*10^3$**
V_R[V]	**900 V**				

Since forward power losses are mainly based on forward current, it is presumed that the largest difference between lowest and highest temperature will be due to the current. This presumption is proved in Tab. V.

Tab. V displays junction tempretarues with same testing currents and frequencies, yet diode reverse voltage achieves only 20 V. On frequencies close to 0 Hz, the difference is unnoticable. The most noticable difference is at 60 kHz where it makes almost 6 °C. The difference between temperatures is practicaly negligible.

TABLE V. TEMPERATURES OF HEAT SINK

I_F [A]	50	150	170	200	f_{SW} [Hz]
T_J [°C]	41,64	78,01	87,38	102,75	**0.00**
	41,64	78,01	87,38	102,75	**500.00**
	41,65	78,02	87,39	102,76	**10^4**
	41,69	78,07	87,44	102,80	**$60*10^3$**
V_R[V]	**20 V**				

D. *Model simulation based on obtained values*

Fig. 5 represents simulation schematic for rectifier circuit. Each diode represents one module containing two Schottky diodes.

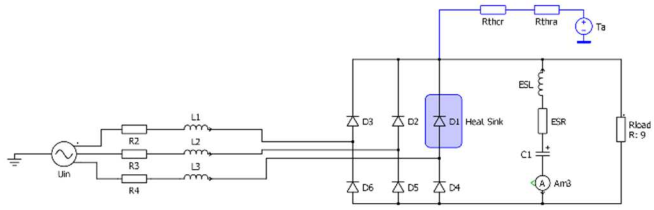

Fig. 5. Schematics of simulated rectifier

Diode thermal model was designed according to datasheet values. Switching frequency is set to 60 kHz and load resistance is selected for maximum current to be 182 A. Based on Tab. III, diode reverse voltage is 900 V. All simulated values are within safe to use values. Starting temperature was set to 100 °C. Simulation outputs are displayed in Fig. 6. Values represented are per leg. Even simulation shows that temperature values are in range of maximal rated ones in datasheet and are similar to calculations. [6]

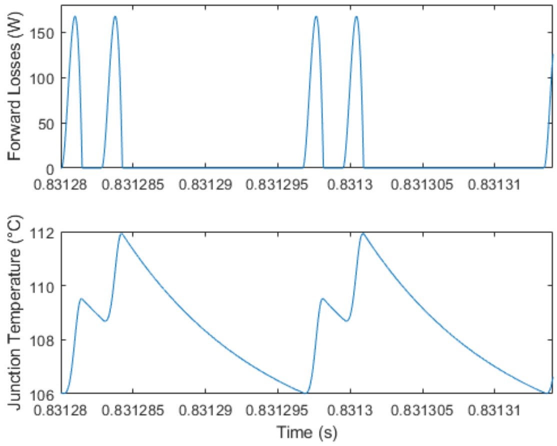

Fig. 6. Simulated forward losses (top) and junction temperature (bottom) of diode reverse voltage of 900 V and diode current of 182 A

As for switching losses, these are shown in Fig. 7 along with diode voltage.

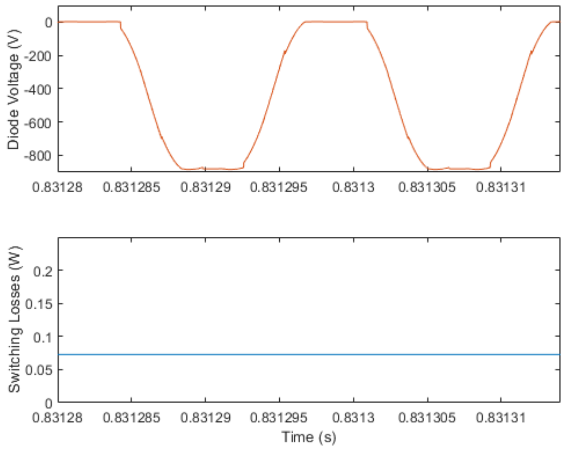

Fig. 7. Simulated voltage (top) and switching losses (bottom) of diode reverse voltage of 900 V and diode current of 182 A

III. Conclusion

There were two proceedings to the calculation of the rectifier parameters. One of the methods was using the simplified equation in (5). Due to this procedure, temperatures in Tab. II were gained. These values gave basic idea of working conditions. Very important was selection of proper heat sink. Mentioned heat sink proved to be sufficient due to its value of thermal resistance.

Second method using equation (1) gave more precise values. With the same cooling component used, junction temperature of the diode module stays below absolute maximum junction temperature even when maximum current was exceeded.

Calculations were then verified via PLECS simulation using self-created diode thermal model. Parameters of heat sink and capacitor were added to the simulation. Output values are shown in Fig. 6 and Fig. 7. Temperature values are very similar to the ones gained by (10).

Next step is to run multiple long-term simulations on various frequencies from 0 Hz to 60 kHz. In parallel with simulations, 3D model design in CAD is being designed. Final step is to build the device based on model.

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