CHAPTER - 6

THERMAL ANALYSIS OF PROPOSED CONVERTER

6.1 INTRODUCTION

Every bidirectional DC-DC converter consists of power switches and it is used to obtain the required performance. In order to obtain the high efficiency, these switches should have low conduction and switching losses. Hence, the switches that are selected for converter should possess the following characteristics. They need to

1. Be highly non-linear and it should enable ZVS turn on and turn off.
2. Have low total gate charge, which in turn leads to have reduced turn on and turn off time.
3. Exhibit low reverse recovery charge $Q_{rr}$ and low reverse recovery time $t_{rr}$.
4. Show low drain to source on-resistance $R_{DS(on)}$ and a low junction to case thermal resistance $R_{th}$. This in turn reduces the conduction loss.

Among these above conditions, the conduction loss occupies a vital role in thermal stability of system. Hence, this chapter discusses the system thermal stability and the output voltage, which are affected by the thermal resistance. This chapter also evaluates the thermal stress on power MOSFET devices during boost and buck mode operation. By this evaluation and with the characteristics of the device, it is possible to predict the junction temperature, the allowable margin of temperature and use of heat sink required to give the suitable thermal margin during operation of converter. This basic method of computation allows more accurate evaluation of system life time and assures working of MOSFET within the Safe Operating Area (SOA) [163]-[165].
6.2 N CHANNEL MOSFET ON STATE RESISTANCE \( R_{DS(on)} \)

As Power MOSFETs are popular for its higher switching speed, it becomes a good choice for the main switching devices in many electrical power conversion systems. But the main problem is it’s ON state resistance and positive temperature coefficient which results in power dissipation and increase in temperature, which is depicted in Fig. 6.1.

![Fig. 6.1 Temperature \( T_J \) versus on state resistance (\( R_{DS(on)} \))](image)

The formula for \( R_{DS(on)} \) in n channel MOSFETs is represented as,

\[
R_{DS(on)} = R_S + R_A + R_{CH} + R_J + R_D + R_{WCML} + R_{SUB} \tag{6.1}
\]

where,

\[
\begin{align*}
R_S &= \text{Source diffusion resistance} \\
R_A &= \text{Accumulation resistance} \\
R_{CH} &= \text{Channel resistance} \\
R_J &= \text{“JFET” component-resistance of the region between the two-body regions} \\
R_D &= \text{Drift region resistance}
\end{align*}
\]
\[ R_{WCML} = \text{Sum of bond wire resistance, the contact resistance between the source and drain metallization and lead frame contributions} \]

\[ R_{SUB} = \text{Substrate resistance.} \]

The normalized value of [166] on state drain source resistance has the ratio between \( R_{DS(on)} \) and \( R_{DS(on)} \) at 25 °C. Equation (6.1) is used for calculation of \( R_{DS(on)} \). From Fig. 6.1, it is observed that doubling of current will result in a 6% increase in \( R_{DS(on)} \). The large variation within the junction temperature might decrease the life of the switches. Hence, the thermal design ought to make sure that the peak temperature is often below the maximum junction temperature. The thermal performance of power devices is simulated in MATLAB.

6.3 EFFECTS OF ‘ON STATE RESISTANCE’ IN PROPOSED CONVERTER IN BOOST MODE

From the data sheet, it is observed that when the \( R_{DS(on)} \) resistance is increased, the junction temperature of the MOSFETs gets increased. The increased value of \( R_{DS(on)} \) also affects output potential and efficiency. Table 6.1 depicts the variations of temperature in the performance of the proposed converter parameters. When temperature increases, efficiency of converter decreases from 84.1 % to 78.8 % because conduction loss across the switches increases. Fig. 6.2 shows the effect of variation of MOSFETs \( R_{DS(on)} \) in accordance with variation in the junction temperature. So on state drain source resistance (\( R_{DS(on)} \)) increases with increase in junction temperature, thereby power loss also increases. Fig. 6.3 shows the changes in converter output voltage when the junction temperature of MOSFETs is varied. From the graph, output voltage decreases due to the increase in temperature. Fig 6.4 shows the effect of increase in junction temperature that leads to the decrease in power output and in turn reduces efficiency of existing and proposed converters.
### Table 6.1 Effect of $R_{DS(on)}$ in converter response

<table>
<thead>
<tr>
<th>Junction Temperature ($^\circ$C)</th>
<th>Normalized $R_{DS(on)}$</th>
<th>$R_{DS(on)}$ (Ω)</th>
<th>Input power (W)</th>
<th>Output voltage (V)</th>
<th>Output power (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>0.55</td>
<td>0.046</td>
<td>97.32</td>
<td>49.6</td>
<td>81.91</td>
<td>84.1</td>
</tr>
<tr>
<td>-20</td>
<td>0.7</td>
<td>0.059</td>
<td>96.54</td>
<td>49.24</td>
<td>80.55</td>
<td>83.4</td>
</tr>
<tr>
<td>0</td>
<td>0.8</td>
<td>0.068</td>
<td>95.95</td>
<td>48.9</td>
<td>79.62</td>
<td>82.9</td>
</tr>
<tr>
<td>20</td>
<td>0.95</td>
<td>0.081</td>
<td>95.15</td>
<td>48.5</td>
<td>78.3</td>
<td>82.2</td>
</tr>
<tr>
<td>40</td>
<td>1.15</td>
<td>0.097</td>
<td>94.2</td>
<td>48</td>
<td>76.7</td>
<td>81.4</td>
</tr>
<tr>
<td>60</td>
<td>1.3</td>
<td>0.11</td>
<td>93.4</td>
<td>47.6</td>
<td>75.4</td>
<td>80.7</td>
</tr>
<tr>
<td>80</td>
<td>1.5</td>
<td>0.127</td>
<td>92.4</td>
<td>47.1</td>
<td>73.8</td>
<td>79.87</td>
</tr>
<tr>
<td>100</td>
<td>1.75</td>
<td>0.148</td>
<td>91.2</td>
<td>46.5</td>
<td>71.9</td>
<td>78.8</td>
</tr>
</tbody>
</table>

### Fig. 6.2 Junction temperature vs $R_{DS(on)}$ comparison
From the results, it is observed that the variation in the junction temperature lowers the efficiency and thermal stability of the system. The output voltage and efficiency of proposed converter gets reduced when there is rise in junction temperature and thermal resistance of the system.
6.4 EFFECTS OF ‘ON STATE RESISTANCE’ IN THE PROPOSED CONVERTER DURING BUCK MODE OF OPERATION

This section deals with the temperature effect during buck mode of operation. Table 6.2 shows the response of non isolated converter in step down mode with variations in $T_j$ and $R_{DS(on)}$.

Table 6.2 $R_{DS(on)}$ variations in converter performance parameters

<table>
<thead>
<tr>
<th>Junction Temperature ($^\circ$C)</th>
<th>Normalized $R_{DS(on)}$</th>
<th>$R_{DS(on)}$ (Ω)</th>
<th>Input power (W)</th>
<th>Output voltage (V)</th>
<th>Output power (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>0.55</td>
<td>0.046</td>
<td>83.2</td>
<td>12.4</td>
<td>76.5</td>
<td>91.94</td>
</tr>
<tr>
<td>-20</td>
<td>0.7</td>
<td>0.059</td>
<td>83.1</td>
<td>12.38</td>
<td>76.4</td>
<td>91.93</td>
</tr>
<tr>
<td>0</td>
<td>0.8</td>
<td>0.068</td>
<td>83.1</td>
<td>12.37</td>
<td>76.2</td>
<td>91.69</td>
</tr>
<tr>
<td>20</td>
<td>0.95</td>
<td>0.081</td>
<td>83.0</td>
<td>12.35</td>
<td>76.1</td>
<td>91.68</td>
</tr>
<tr>
<td>40</td>
<td>1.15</td>
<td>0.097</td>
<td>82.9</td>
<td>12.34</td>
<td>75.9</td>
<td>91.55</td>
</tr>
<tr>
<td>60</td>
<td>1.3</td>
<td>0.11</td>
<td>82.9</td>
<td>12.33</td>
<td>75.8</td>
<td>91.43</td>
</tr>
<tr>
<td>80</td>
<td>1.5</td>
<td>0.127</td>
<td>82.8</td>
<td>12.31</td>
<td>75.6</td>
<td>91.27</td>
</tr>
<tr>
<td>100</td>
<td>1.75</td>
<td>0.148</td>
<td>82.7</td>
<td>12.29</td>
<td>75.3</td>
<td>91.05</td>
</tr>
</tbody>
</table>

Fig. 6.5 shows the effect of variation of MOSFETs $R_{DS(on)}$ in accordance with variation in the junction temperature. Fig. 6.6 illustrates variation in output voltage with change in junction temperature of MOSFET. Simulation results exhibit the variation in the junction temperature of the power switches that lowers the efficiency from 91.94 % to 91.05 %. Fig. 6.7 illustrates converter output power and efficiency of existing and proposed converters that decreases with increase in junction temperatures. From the Figures, it is clear that the output voltage and power are more when compared to the existing one even under variations in temperature occurs. Hence it is concluded that the proposed converter will achieve improved efficiency even there is change in temperature.
Fig. 6.5 $R_{DS(on)}$ versus junction temperature

Fig. 6.6 Comparison graph of junction temperature and output voltage
The variation in loss, results in corresponding change in temperature of MOSFET. Fig. 6.8 shows the energy losses occurred during switching in boost and buck operation. The slope of energy-loss curve gives the power loss in switches. The power loss is the sum of conduction and switching losses. Simulation is carried out at 125 °C, which indicates hard switching of switches.
The maximum power dissipation \( P_{D(max)} \) at thermal equilibrium is given in equation (6.2).

\[
P_{D(max)}(T_a) = \frac{T_{ch(max)} - T_a}{R_{th(ch-a)}}
\]  

(6.2)

where

- \( T_a \) - Ambient temperature,
- \( T_{ch(max)} \) - Maximum channel temperature,
- \( R_{th(ch-a)} \) - Channel-to-ambient thermal resistance.

Fig. 6.9 shows the switching loss during turn on and off at different temperatures 25°C and 125°C. From the graph it is observed that when temperature increases switching losses also increases. Hence, care is taken in MOSFET thermal design to make sure \( T_{ch(peak)} \) does not exceed \( T_{ch(max)} \).

![Fig. 6.9 Load current versus loss per switching event](image-url)
Heat sink enhances the thermal stability of switches during temperature variations, which is discussed in following section 6.5

6.5 DESIGN OF HEAT SINK

The effect of increase in temperature is sorted out by proper design of heat sink. Heat sinks are the devices, which are implemented in the practical applications to cool down the semiconductor devices by convection and radiation process. The semiconductor devices do not have the capacity to fully dissipate the heat generated by it. This thermal effect will affect the life of switches and create thermal runaway problem. Therefore an aluminum heat sink is utilized to get rid of thermal effect.

6.5.1 Selection of a heat sink

Heat sink is evaluated based on the amount of heat that they can dissipate. Heat sink manufacturer data sheets deliver the details about the thermal resistances for natural convection and various air flow velocities, before choosing a heat sink for MOSFETs.

Initially, the calculation of power dissipation of components present in the circuit is carried out. Power dissipation can be obtained from the efficiency measurements. Once the total power loss is obtained, the thermal resistance of the heat sink is calculated using equation (6.3) and its equivalent circuit indicates duality of electric resistance with thermal impedance as shown in Fig. 6.10. The parameters of the thermal models are tuned to give the equivalent results.

\[ R_{\theta_{JA}} = R_{\theta_{JC}} + R_{\theta_{CS}} + R_{\theta_{SA}} \]  

(6.3)

where,

\( R_{\theta_{JC}} \) - Junction to case thermal resistance of the power device

\( R_{\theta_{CS}} \) - Case to heat sink thermal resistance

\( R_{\theta_{SA}} \) - Heat sink to ambient thermal resistance
Fig. 6.10 Equivalent circuit of a heat sink

With the help of these resistors, the junction temperature of the MOSFET can be obtained as in eqn. (6.4)

\[ T_j = P(R_{\theta_{jc}} + R_{\theta_{cs}} + R_{\theta_{sa}}) + T_a \]  

(6.4)

where

\( P \) - Power from which the heat dissipation is attempted

\( T_a \) - Ambient Temperature

Based on the junction temperature of the switching devices, the heat sink is chosen. Thus, the proper design of heat sink will increase the thermal stability of the system.

### 6.5.2 Design of heat sink for proposed converter switches

#### 6.5.2.1 Boost switch heat sink design

Consider junction temperature at \( T_j = 80 \, ^\circ C \), power loss is \( P = 18.6 \, W \), ambient temperature \( T_a = 33 \, ^\circ C \), from MOSFET IRF540 data sheet, \( R_{\theta_{jc}} = 1 \, (^\circ C/W) \) and \( R_{\theta_{cs}} = 0.5(^\circ C/W) \). Substituting these values in equation (6.4), thermal resistance between heat sink to ambient \( R_{\theta_{sa}} \) is 1.03(\(^\circ C/W\)).

#### 6.5.2.2 Buck switch heat sink design

Consider junction temperature at \( T_j = 80 \, ^\circ C \), power loss is \( P = 7.3 \, W \) watts, ambient temperature \( T_a = 33 \, ^\circ C \), from IRL3215 data sheet, \( R_{\theta_{jc}} = 1.9 \, (^\circ C/W) \) and \( R_{\theta_{cs}} = 0.5(^\circ C/W) \). Substituting these values in equation (6.4), thermal resistance between heat sink to ambient \( R_{\theta_{sa}} \) is 4.04(\(^\circ C/W\)).

From the heat sink design calculation the material for heat sink chosen for proposed converter is found to be aluminum.
6.5.3 Layout considerations for the position of heat sink

Fig. 6.11 illustrates the thermal resistance of MOSFET placed perpendicularly at core of the heat sink. It indicates comparison between heat sink material such as aluminum, copper and steel sheet. From the comparison, aluminum material provides fast heat dissipation compared to other material.

![Fig. 6.11 Area of heat sink and thermal resistance of a MOSFET](image)

**Fig. 6.11 Area of heat sink and thermal resistance of a MOSFET**

Now days, different thermal heat sink are available. A numerous factors have to be considered when integrating heat sink in a circuit layout which includes height, available space and air flow. So while selecting heat sink for the power switches, the manufacturer recommendations have to be followed in for spacing and positioning of the heat sink in the circuit. Heat sink increases reliability by extending the life of N channel MOSFET switches.

6.6 SUMMARY

This chapter discussed the effect of temperature variations of power switches over the performance measures of converter such as voltage, power and efficiency of the system. Heat sink is designed to improve the thermal stability in turn minimizes the effect of temperature. Based on the junction temperature of the switching devices, the evaluation of power loss is carried out and heat sink is designed for boost and buck mode switches. The thermal analysis helps to predict the right choice of heat sink to operate in safe manner by restricting the area of the power losses in the switch device.