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Use of Thermal Zones as a Technique to Optimize Evaluation of a High-Temperature Bidirectional Converter

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Abstract. Current electrical component technology makes it impossible for entire systems to operate at the extreme temperatures required for many applications. Therefore, thermal zoning is a straightforward method to maximize the temperature capability of complex systems. The technique involves simple thermal analyses to determine variable temperature limits, design requirements, and cooling techniques for an electrical system. This paper discusses how the thermal zoning technique is used during program development in order to maximize the demonstration temperature of a 50 kW bidirectional converter.

1. Introduction

Due to the complex interaction between cooling and power dissipation within an electrical assembly it can be difficult to find the limiting factor for a thermal design. In many cases attempts to improve component capabilities can be detrimental to the overall design. The thermal zoning technique is a straightforward eight step procedure, outlined in Table 1, which involves simple designs, thermal analyses, and a little research.

Table 1: 8-Step Thermal Zoning Technique

Step	Definition
1	Create a preliminary design
2	Divide the assembly into thermal zones
3	Define the thermal circuit
4	Review zones
5	Solve circuit
6	Determine capability of zones
7	Iterate zone capability based upon limits
8	Check results

A 50kW bidirectional converter is under development to demonstrate continuous functional capability with cold source temperatures in excess of 200ºC, and a goal of achieving 250ºC. As this 50kW bidirectional converter program is a technology demonstrator (TRL3) the intended goal is gaining practical experience with the components, interconnections, cooling technologies, manufacturing techniques, and materials required for operation at extreme temperatures. A block diagram of the system is shown in Figure 1.

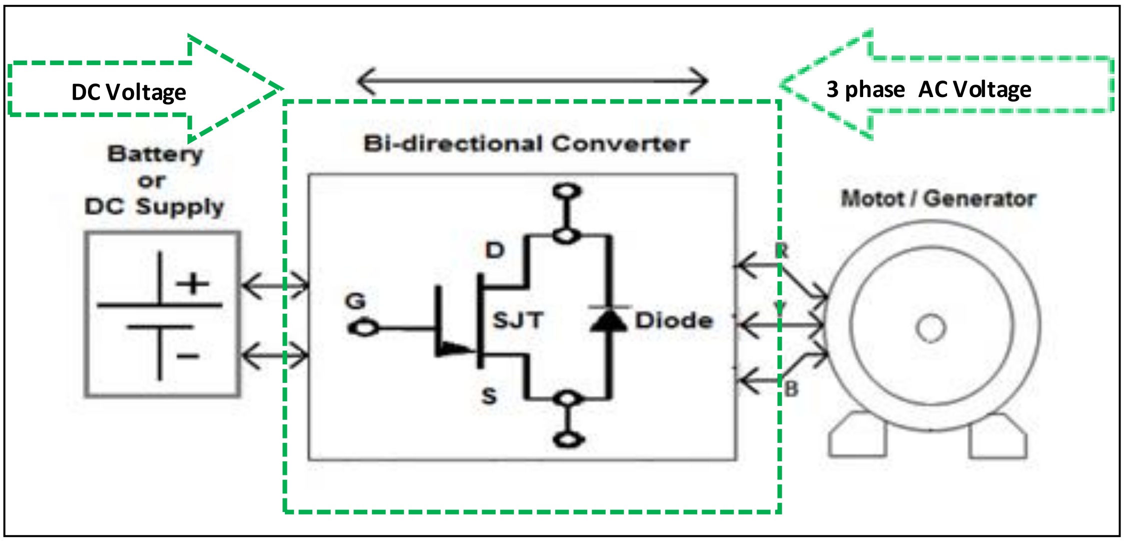

Figure 1: Block Diagram of a 50 kW Bidirectional Converter

2. Bidirectional Converter System

The first two steps in applying the Thermal Zoning Technique are creating a preliminary design of the system and dividing it into a set of thermal zones. A preliminary interconnect for the bidirectional converter is shown in Figure 2. The bidirectional converter system's five temperature zones: High Temperature Ambient, Power Bridge, Power Board, Control Board, and Low Temperature Ambient, are based upon the mechanical and electrical partitioning used to define the interconnects. The Power Bridge zone is a set of electrical assemblies used for electrical conversion. The Power Board zone is a printed wiring assembly used to filter, measure, and condition the electrical power. Control of the system is completed in the Control Board zone on a printed wiring assembly. The High Temperature Ambient zone is the air space around the Power Board and Power Bridge, but outside the Temperature Controlled Enclosure. Similarly, the Low Temperature Ambient zone is the general lab area where the system will be installed.

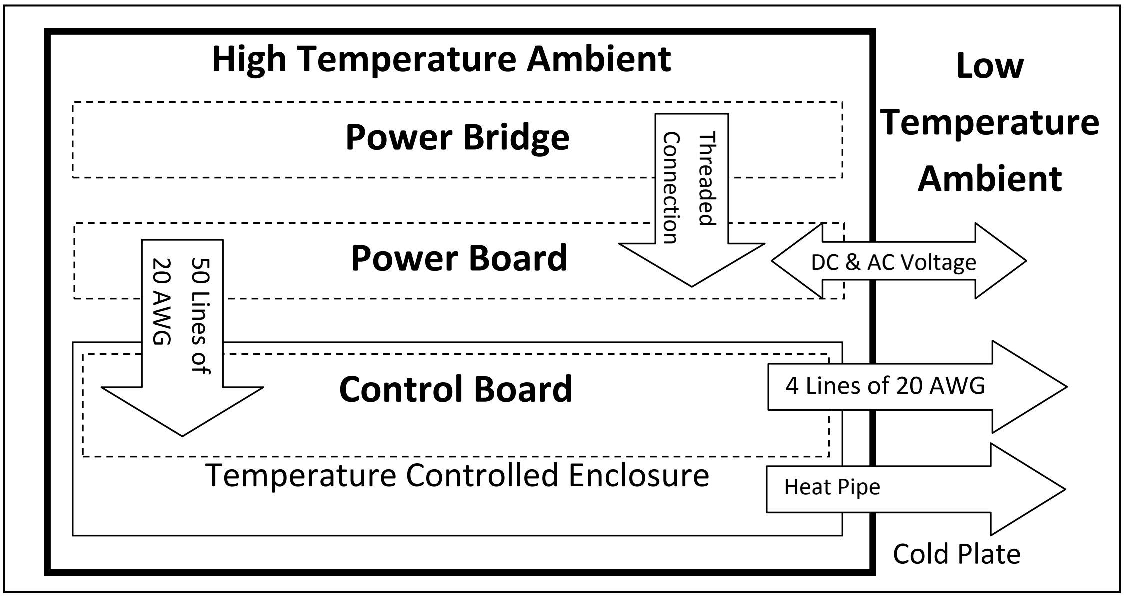

Figure 2: Representation of the Thermal Zones and Interconnections

Figure 3 represents the initial physical layout for the bidirectional converter assembly. In this design the Power Bridge is split into four identical assemblies which are mounted to a piece of fin stock for improved cooling. Each Power Bridge is mounted to the Power Board with five steel threaded connections. Fifty 20AWG wires form the control cable used to carry electrical signals between the Control Board and the Power Board. Heavy gauge wire will bring the AC and DC Voltage to the Power Board via the power cable. Due to limited temperature capability of the intricate devices used on the Controller Board, this zone represents the greatest thermal challenge. Therefore, a temperature controlled enclosure thermally isolates the Control Board from the rest of the system. Nevertheless, the enclosure has access for the control cable running between the Control and Power Boards. Two additional cutouts are included in the temperature controlled enclosure to allow a 4-wire signal cable and the loop heat pipe (LHP) to exit the thermal chamber.

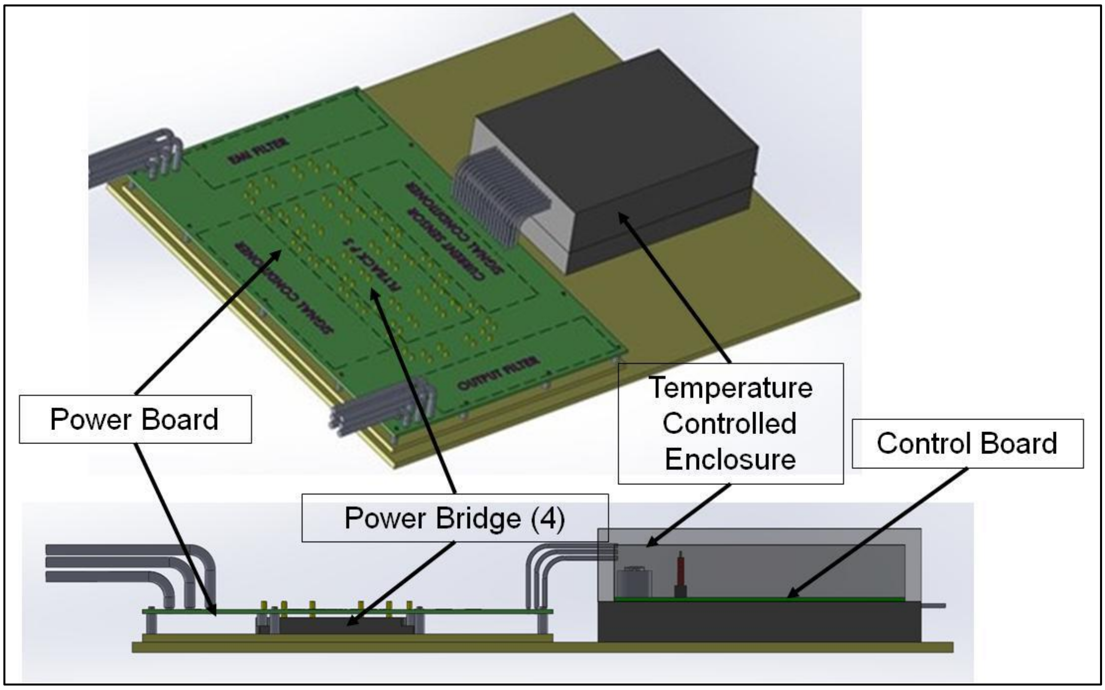

Figure 3: Bidirectional Converter System Mechanical Concept

3. Thermal Analysis

Step 3 of the Thermal Zoning Technique is a simple thermal analysis. Two cold sources are available for cooling the bidirectional converter system. The air within the thermal oven, referred to as the High Temperature Ambient zone, will be the cold source for the Power Bridge and the Power Board. The expected heat flow for these two assemblies under normal operating conditions is between 1.75 and 3 kW. The Control Board will also be mounted within the High Temperature Ambient zone, but unlike the Power Board and Power Bridge, insulation will be used to keep the High Temperature Ambient from heating the Control Board. The Low Temperature Ambient zone will be coupled via LHP to the Control Board and used as the cold source. This low temperature zone is external to the thermal chamber and in the general lab area.

Figure 4 is a circuit representing the thermal interconnections between the Power Bridge, Power Board, and High Temperature Ambient thermal zones. In this figure the power bridge dissipations are represented as current sources “B1,” “B2,” “B3,” and “B4” while “P” represents another current source equal to the power dissipation on the Power Board. Each of the six resistor reference designators identifies a specific path available for heat transfer. Finally, the High Temperature Ambient zone is represented as ground in this circuit. Since forced convection will be the dominant source of system cooling the initial thermal analysis ignores the effects of radiation. This is not considered to be a significant risk to the program because radiant cooling will increase the energy transfer from the system and improve its maximum operating temperature. Nevertheless, should a designer wish to include the effects of radiant cooling explicitly in the analysis this thermal path would also be included as a resistor.

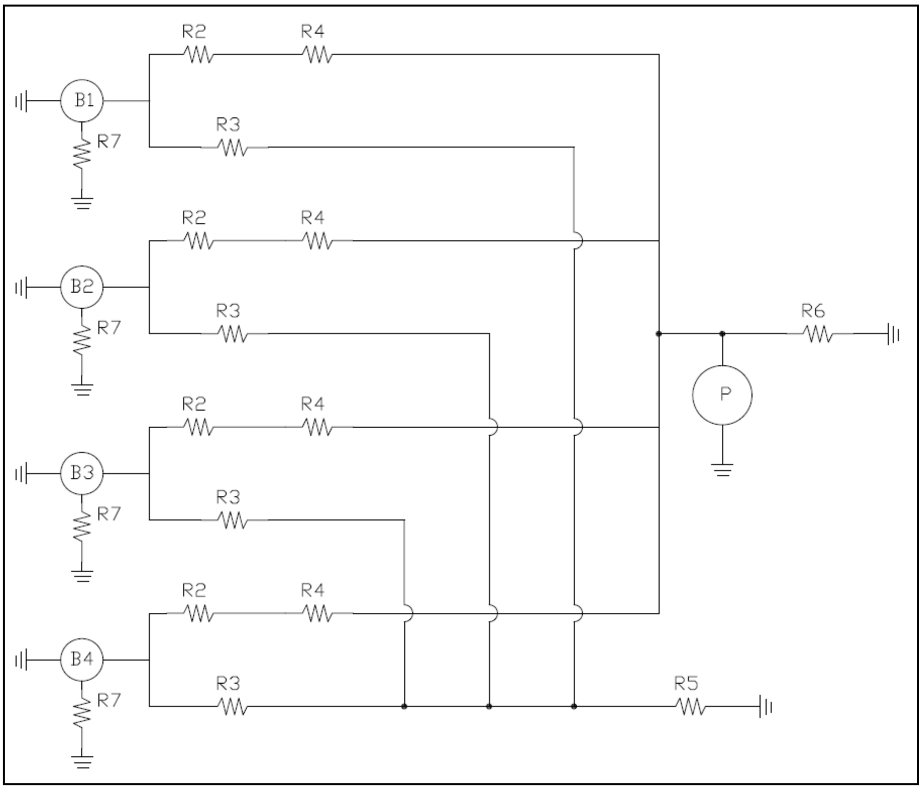

Figure 4: Thermal Circuit for the Bidirectional Converter

The Control Board has a minimal number of powered components, and is isolated from the High Temperature Ambient and the Power Board. Although it does represent another parallel path for heat rejection, the control cable is assumed to be insulated and of sufficient length to conduct a negligible amount of heat. Thus, it has been removed from the Power Board and Power Bridge thermal analysis. The heat transfer along the control cable becomes significant when the system is viewed from the perspective of the Control Board. For this reason, a detailed discussion of the Controller Board and Temperature Controlled Enclosure study is included in Section 4.5. Nevertheless, simplifying the system to remove any impact of the Control Board and temperature controlled enclosure should be marginally conservative for the remaining thermal zones.

With a thermal resistance values, power levels, and a fully developed thermal circuit the resultant temperature increases can be calculated. Software such as PSPICE, Simetrix, Orcad, or other programs supplied by component manufacturers will quickly solve the circuit. Power levels shown in Table 2 are based upon the 96% minimum system efficiency expected for the converter. The Power Bridge represents the largest source of waste heat in the bidirectional converter; therefore, approximately 95% of the power dissipation has been allocated to the four Power Bridges. Junction to case thermal resistances, included as R1, are a consequence of the particular die packaging used during component manufacturing. As this is a finer detail than required by a preliminary zoning study it has been neglected. The remaining thermal resistances are calculated from the interface resistivity in [1] and the material properties in [2]. This analysis assumes a constant temperature in each thermal zone. Therefore, to ensure that localized heating does not create failures, when determining the appropriateness of a component or material for use in a particular zone design factors must be used.

Although it was not included in the preliminary design represented in Figure 3, a resistance value for direct convection off the Power Bridge and into the High Temperature Ambient was included in the thermal analysis. This additional thermal path allowed for a change in the mounting configuration if temperatures on the Power Bridge became too great. However, results in Table 2 show that power dissipated directly from the Power Bridge and into the High Temperature Ambient is negligible. As a result, the board surface area is better used for cooling the Power Board and the mounting of components as originally designed.

Table 2: Thermal Circuit Solution

Resistor	Resistance	Power	ΔT	Notes
(#)	(ºC/W)	(W)	(ºC)	
1	0	472.5	0.00	Conduction from component to Power Bridge (θ_{JC})
2	5.25	8.25	43.31	Conduction along Power Bridge to Power Board interface
3	0.026	460.3	12.04	Conduction from Power Bridge and into Fin Stock
4	0.034	8.25	0.28	Conduction from Power Bridge and into Power Board
5	0.032	1841.0	59.67	Convection off of Fin Stock
6	0.206	133.0	27.40	Convection off of Power Board
7	17.71	4.00	70.86	Convection directly off of the Power Bridge

4. Capability of the Thermal Zones

The Thermal Zoning Technique's sixth step is determining capabilities for each thermal zone. Understanding what limiting factors exist for a particular thermal zone allows developers to avoid paying for unnecessary capability in other areas of the assembly. With the calculated temperature deltas in Table 2, it is possible to iterate the selection of materials, components, and cold source temperatures until the weakest link in the system is determined. This iteration is Step 7 in the Thermal Zoning Technique.

4.1. Low Temperature Ambient

Test and support equipment required for the bidirectional converter to operate will be located in the Low Temperature Ambient zone. This is a large general lab area which will have active temperature control using facility heating, venting, and cooling (HVAC) systems to maintain a roughly 20ºC ambient. Heating in this zone is expected to be the result of less than 100 W; this represents control power dissipation, wild heat from the thermal chamber, and power losses from the support equipment. This zone does not represent a limiting factor on the bidirectional test temperature.

4.2. High Temperature Ambient

The High Temperature Ambient zone will be created by a thermal chamber and represents the primary cold sink for the bidirectional converter assembly. The thermal chamber has an active control system which causes the temperature of the High Temperature Ambient to be constant and known. Therefore, cooling capability for the Power Bridge and the Power Board is not limited by the capacitance of the air. Expected heat flow in the High Temperature Ambient zone is approximately 2 kW, but may be as large as 3 kW. A limitation of the thermal chamber means that the High Temperature Ambient zone cannot exceed 200 ºC and still be actively controlled [3]. However, the temperature of the fin stock used for cooling the Power Bridge will be notably higher due the heat flow from the power electronics. This zone is not expected to represent a limit on the bidirectional test temperature.

4.3. Power Bridge

The zone referred to as the Power Bridge is an assembly which contains the 3-Phase electrical bridge assemblies, diodes, and inductors. With expected power dissipation levels just below 475 W per bridge, at 96% system efficiency, the total surface heat flux exceeds 12 W/cm^2, and heat flux levels for the powered components approach 50 W/cm^2. Nevertheless, as they are self-heating, powered component must be robust for extreme thermal environments.

A breakdown of the maximum operational temperatures for components, materials, and interconnects used in the Power Bridge are shown in Table 3. Based upon program development testing, the use of silicon-carbide diodes and super junction transistors [4] increases the operational temperature range significantly above the operational limits of commercially available silicon components [5]. Similarly, reconfiguring the design to move inductors out of the Power Bridge and onto the Power Board also improves the thermal capability of the Power Bridge. Finally, eutectic gold-tin solder (Au80Sn20) can be used for most interconnections within the Power Bridge. Although the eutectic temperature for this solder is only 280 ºC, the rework and operational limits can be much higher. After application to gold leaded components the reflow temperature of eutectic gold-tin solder increases to 320 ºC which is sufficient to provide margin over expected Power Bridge temperatures [6]. Nevertheless, limited brazing and wire bonding will be used at locations such as the threaded inserts where high strength is required.

Table 3: Temperature Limits within the Power Bridge

Description	Max Temp (ºC)
Interconnection	
Eutectic gold-tin solder	320
Components	
SiC Diodes	250
SiC Super Junction Transistors	250
Temperature Sensors	280
Inductors	200

4.4. Power Board

The Power Board is the most complex portion of the bidirectional converter. In addition to interfacing directly with the Power Bridge assemblies, the Power Board will contain AC/DC current sensors, electrical filtering, link capacitors, auxiliary power supplies, inductors, and gate drivers. Cooling of the Power Board will occur via a small amount of forced convection produced by the thermal chamber control system and fan/blower. Depending upon the assumed geometry and the temperature differential, forced convection of air will result in a heat transfer coefficient between 25 and 250 W/m^{2}K [2]. Therefore, the convective heat transfer coefficient for the Power Board to High Temperature Ambient zone is assumed to be 25 W/m^{2}K. The high temperatures used within the thermal chamber and the complex geometries created by components mounted on the PWA justify using a heat convection coefficient value on the lowest end of the range defined for forced convection.

Component technology for the devices mounted on the Power Board varies greatly. Included in Table 4 is the breakdown of maximum operational temperatures for components, materials, and interconnects used in the Power Board. Operational temperature ranges for capacitors [7], resistors [9], thermal sensors, and laminates [10] can vary by several hundred degrees. However, the temperature capability of passive devices, such as inductors and other magnetics, are limited to 150ºC [5] which can be increased slightly by modifying the materials and manufacturing processes used in assembly. Furthermore, by carefully laying out the board with these less capable components placed further from the Power Bridge connections and powered devices the temperature capability of the Power Board can be improved. Furthermore, limited cooling technologies, such as heat sinks, may be implemented to locally decrease device temperatures where local heating or hot spots lead to inadequate operational temperature potential. Finally, despite a high temperature tin-silver solder having an apparently acceptable temperature limit for the Power Bridge [11], local heating and hot spots make gold-tin solder preferable.

Table 4: Temperature Limits within the Power Board

Description	Max Temp (ºC)
Board Material	
Glass reinforced hydrocarbon/ceramic laminates	280
Interconnection	
Eutectic gold-tin solder	320
High temperature tin-silver solder	221
Components	
Inductors & other magnetics	200
Capacitors	200
Temperature Sensors	280
CAN Driver	210
Gate Driver	230
Logic Integrated Circuits	225

4.5. Controller Board

Signal conditioning circuitry, power supplies, voltage sensors, connectors, and integrated circuits will all be mounted on the Controller Board. Limited temperature capability of the intricate devices used on the Controller Board makes this zone the greatest thermal challenge. A temperature controlled enclosure isolates the Control Board from the rest of the system to keep the device temperatures below 80ºC. The enclosure does have access for the Control Cable between the Control and Power Boards. The control of temperature inside this box has been chosen to be a two-phase device using heat pipe technology.

Heat pipe technology consists of the transport of thermal power from a hot dissipating point to a remote cold source through the latent heat characteristic of a working fluid. As classical heat pipes would fail to operate in very severe conditions and on geometrically complex solution, LHP technology allows overcoming these limiting aspects thanks to the use of very fine and efficient porous media as capillary pump ([12], [13]). This operating principle is described briefly on Figure 5.

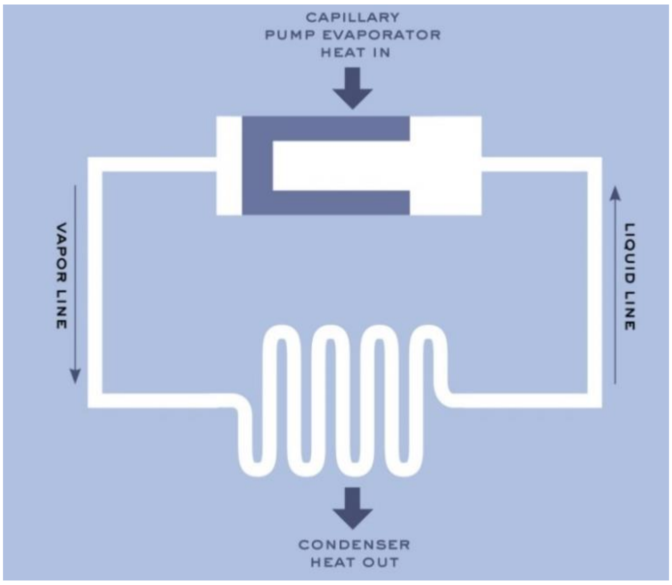

Figure 5: LHP operating principle

Multiple motivations raise the choice of heat pipe technology to cool down the Control Board. First of all, an efficient cooling solution is needed to maintain the insulated box temperature under 80°C according to available cold sources (ambient air at lab condition or cold plate). A heat pipe reduces to its lowest value the thermal resistance between the cold source and the Control Board, reducing at the minimum the Board temperature. In addition, this lab test set-up shall demonstrate the ability of heat pipe technology to manage severe ambient condition which could disturb, significantly or not, the operating of the fluid loop. Finally the two-phase technology offers a passive way to bring the heat to the cold source and so improves reliability and reduces the operating costs (no active pump or fan).

The greatest challenge lie in dealing with all possible parasitic heat fluxes which should disturb the insulated box thermal balance: the convective and radiative heat flux coming from the High ambient temperature zone, the heat flux coming from connection wires and the parasitic heat on the path of the heat pipe through the high ambient zone. Finally, the sum of all parasitic heat fluxes will be largely greater than the heat to extract from the Control Board. The insulation of critical parts of the two-phase device as well as the whole temperature controlled enclosure is in development to propose a solution based on a fine thermal analysis of the system composed of the LHP and the temperature controlled box.

5. Conclusion

Using the thermal zoning technique, the Control Board was identified as the initial thermal challenge on the 50 kW bidirectional converter under design. The issue of very low temperature capability for components mounted on the Control Board via the concept of a LHP coupled to the Low Temperature Ambient zone. The next weak link becomes the Power Board. Particular areas of concern for the Power Board are passive components such as magnetics and capacitors.

As shown in Table 5, based upon the assumed 96% efficiency and the limiting temperatures of each zone, the demonstration test can be completed at 225ºC provided the High Temperature Ambient is set at 150ºC. On the other hand, the large power dissipation into the Fin Stock causes the Power Bridge to see an effective cold source temperature of approximately 209ºC. These parameters achieve the stated demonstration goal. Unfortunately, demonstrating functionality at higher cold source temperatures will place components on the Power Bridge at risk.

Table 5: Resultant Temperatures by Zone for 96% Efficiency

Zone	Power (W)	Temp (ºC)
High Temperature Ambient (Air)	0	150.0
High Temperature Ambient (Finstock)	0	209.2
Low Temperature Ambient	0	25.0
Control Board	10	80.0
Power Bridge	1890	221.2
Power Board	100	180.2

A bidirectional converter with an overall efficiency at 94%, but maintaining the 100 W Power Board dissipation level will increase the Fin Stock temperature without significantly increasing the Power Board temperature. As a result, when the High Temperature Ambient air is at 150ºC components mounted on the Power Bridge will be exposed to mounting surface temperatures near 250ºC. The Power Board temperature in this configuration will remain between 185 to 220ºC depending upon localized heating and hot spots. These results are shown in Table 6.

Table 6: Resultant Temperatures by Zone for 94% Efficiency

Zone	Power (W)	Temp (ºC)
High Temperature Ambient (Air)	0	150.0
High Temperature Ambient (Finstock)	0	240.6
Low Temperature Ambient	0	25.0
Control Board	10	80.0
Power Bridge	2890	258.8
Power Board	100	185.3

Current electrical component technology makes it impossible for the entire bidirectional converter to operate with a 200 to 250ºC temperature cold source. However, it is difficult to predict the weakest link in the system. Thermal zoning is a straightforward technique which involves simple thermal analyses to determine variable temperature limits, design requirements, and cooling techniques for an electrical system. The technique prioritizes problems for solutions and may lead to such counter intuitive results as less efficient Power Bridges are the most effective path forward for a technology demonstrator.

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