SAND2010-8907P

MODULAR MACRO INVERTER FOR “INTELLIGENT POWER CONTROLLERS FOR SELF-ORGANIZING MICROGRIDS [*]

S.F. Glover, F.E. White, S.V. Spires

February 2, 2009

[*] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

TABLE OF CONTENTS

I. INTRODUCTION

Power electronic based inverters have proven to be a key element to the connection of renewable resources to the grid. Research into the control of these inverters needs to improve load sharing capabilities, islanding capabilities, reliability, and greater understanding of sources that are close in proximity. The inverter design presented in this document has been setup as a research platform for further research into reliable renewable energy resources. The power supply presented below is referred to as a modular macro inverter (MMI). The design requirements for the MMI are listed in Table I below.

Table I. Design Requirements

1	The MMI shall be attachable to a solar panel.
2	The MMI shall supply up 1kW or greater of power.
3	The MMI shall be capable of operating over a DC voltage input range of 12V to 48V
4	The MMI shall be capable of outputting a 60 Hz, 120 Vrms waveform.
5	The MMI shall be controllable to the switching level.
6	The MMI should be designed so that it could self charge from the output side of the power supply.
7	The control design will be performed separate from the hardware design and therefore is not included in this document.
8	An average value circuit model shall be included for control development
9	The MMI should be constructed by the end of FY08 if resources permit.

The actual MMI specifications after completion of the design are listed in Table II. Note that the power and voltage range requirements have been met. This power supply can run off of a DC source solar panels included. Direct control over the IGBTs is also a design feature allowing the future control design to operate down to the switching level.

Table II. Design Specifications

Input voltage range	0 – 250V
Maximum power	1.2 kW
Maximum boost converter switching frequency	10kHz
Maximum inverter switching frequency	10kHz
DC isolated output (minimum)	300V
Maximum DC link voltage	250 V
Maximum input current	25 A
Maximum output current	10 Arms
Output voltage	120 Vrms

The power electronics reference used throughout this design was Mohan [1]. All analysis and simulations presented below were performed using MatLab [2].

A. Circuit Model

The circuit diagram is provided in Figure 1 and includes blocks representing the controllers. The circuit parameters are listed in Table III and are followed by the differential equations that describe the behavior of the circuit. Heaviside's notation is used in the equations. That is $px = dx/dt$.

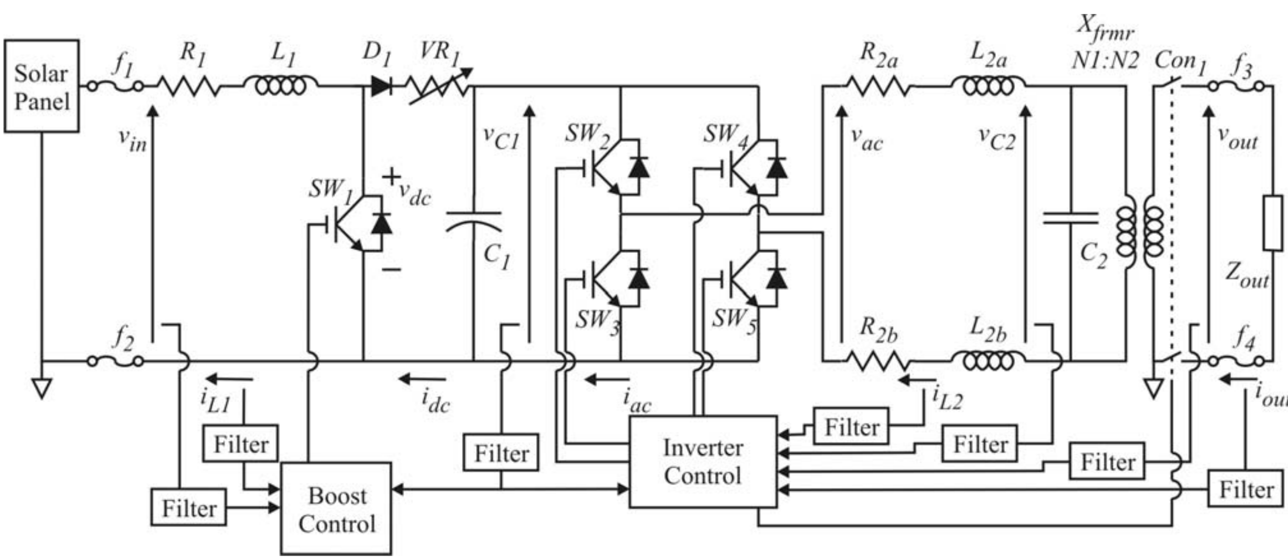


Figure 1. MMI circuit model.

Table III. Circuit Parameter Values

Resistance of L_1	R_1	<15 mΩ
Resistance of L_{2a}	R_{2a}	15 mΩ
Resistance of L_{2b}	R_{2b}	15 mΩ
Thermistor[1]	VR_1	18.5 mΩ – 1 Ω 214 °C – 25 °C
Boost inductance[2]	L_1	1 mH
Filter inductance[2]	L_{2a}	1 mH
Filter inductance[2]	L_{2b}	1 mH
DC link capacitance	C_1	4.2 mF
Filter capacitance	C_2	35 µF
Isolation transformer	X_{frmr}	1:1
Input fuse	f_1, f_2	35 Adc
Output fuse	f_3, f_4	10 Arms

[1] The thermistor is in series with D_1 and C_1 to act as a in rush current limiter, two devices are in parallel.

[2] Note that the inductors were vacuum impregnated with epoxy to reduce the audible noise [3].

The derivative of the current through L_1 is

$$pi_{L1} = \frac{(v_{in} - i_{L1}R_1 - v_{dc})}{L_1}, \tag{1}$$

where v_{dc} is the voltage across SW_1. The derivative of the voltage across C_1 is

$$pv_{C1} = \frac{(i_{dc} - i_{ac})}{C_1}, \tag{2}$$

where i_{dc} is the current flowing through D_1 and i_{ac} is the current into the inverter. The derivative of the current through L_2 is

$$pi_{L2} = \frac{(v_{ac} - i_{L2}R_2 - v_{C2})}{L_2}, \tag{3}$$

where v_{ac} is the voltage at the output of the inverter, L_2 is the total inductance of the filter

$$L_2 = L_{2a} + L_{2b}, \tag{4}$$

and R_2 is the total resistance of the filter inductor

$$R_2 = R_{2a} + R_{2b}. \tag{5}$$

The derivative of the voltage across C_2 is

$$pv_{C2} = \frac{(i_{L2} - i_{out}N1N2)}{C_2}, \tag{6}$$

where $N1N2$ is the turns ratio of X_{frmr}. The voltage at the output side of the contactor, Con_1, is

$$v_{out} = v_{C2}N1N2. \tag{7}$$

The current out of the MMI is defined as

$$i_{out} = \frac{v_{out}}{Z_{out}}. \tag{8}$$

B. Average Value Model (Continuous operation)

The average value model of the MMI allows for simulating the system without introducing harmonics created by switching events. The circuit parameter values are the same as those listed for the circuit diagram in the previous section and are listed in Table III. The equations for the average value model are provided below and are dependent upon whether the MMI boost converter is operating in a continuous or discontinuous mode of operation. The equations presented below only represent the continuous mode of operation.

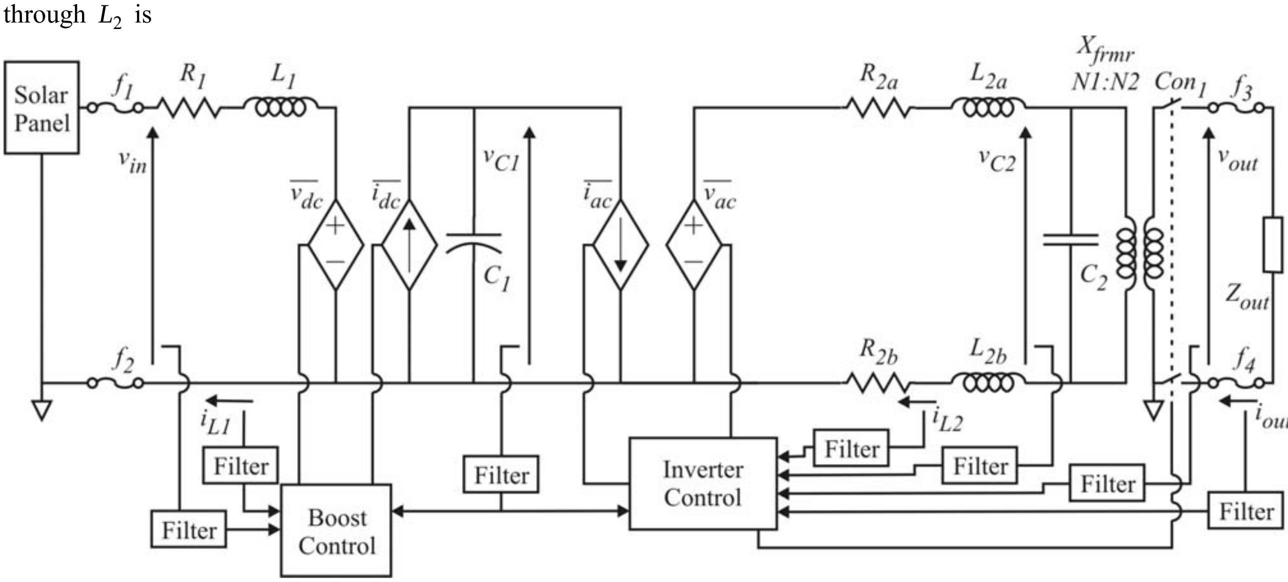


Figure 2. MMI average value model.

The derivative of the current through L_1 is

$$pi_{L1} = \frac{(v_{in} - i_{L1}R_1 - \overline{v_{dc}})}{L_1}, \quad (9)$$

where $\overline{v_{dc}}$ is the average value of the voltage across SW_1 and is defined as

$$\overline{v_{dc}} = v_{C1}(1-D), \quad (10)$$

where v_{C1} is the voltage across C_1 and D is or duty ratio. The derivative of the voltage across C_1 is

$$pv_{C1} = \frac{(\overline{i_{dc}} - \overline{i_{ac}})}{C_1}, \quad (11)$$

where $\overline{i_{dc}}$ is the average value of the current out of the boost converter and $\overline{i_{ac}}$ is the average value of the current into the inverter. $\overline{i_{dc}}$ is defined as

$$\overline{i_{dc}} = i_{L1}(1-D) \quad (12)$$

and $\overline{i_{ac}}$ is defined as

$$\overline{i_{ac}} = \frac{\overline{v_{ac}}\, i_{L2}}{v_{C1}}. \quad (13)$$

The derivative of the current through L_2 is

$$pi_{L2} = \frac{(\overline{v_{ac}} - i_{L2}R_2 - v_{C2})}{L_2}, \quad (14)$$

where the total inductance of the filter, L_2, is defined in (4), the resistance R_2 is defined in (5), and $\overline{v_{ac}}$ is the average value of the voltage across the output of the inverter defined by

$$\overline{v_{ac}} = m v_{C1} \sin(\varpi_1 t + \theta), \quad (15)$$

where m is the amplitude modulation ratio, ϖ_1 is the fundamental frequency of the output, and θ is the phase angle of the output waveform. The derivative of the voltage across C_2 is

$$pv_{C2} = \frac{(i_{L2} - i_{out} N1N2)}{C_2}, \quad (16)$$

where $N1N2$ is the turns ratio of X_{frmr}.

The average value model of the MMI was simulated using Matlab [2] and a very crude control design. The results are plotted in Figure 3 through Figure 5. Note that this average value model only represents the continuous mode of operation. Most parasitic effects are not represented in this model except for the resistance of the inductors. All other parasitics and the thermistor R_t are not represented in the simulation.

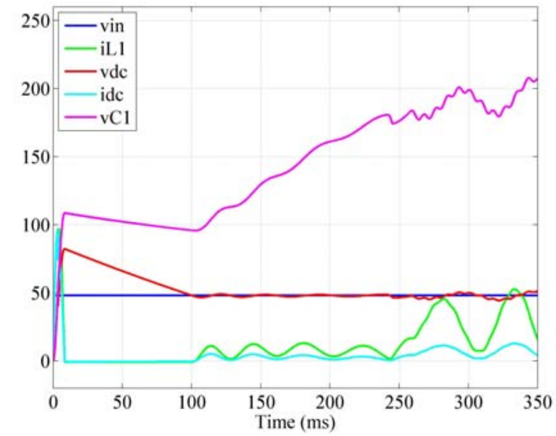


Figure 3. Example simulation results of the average value model. Boost converter waveforms.

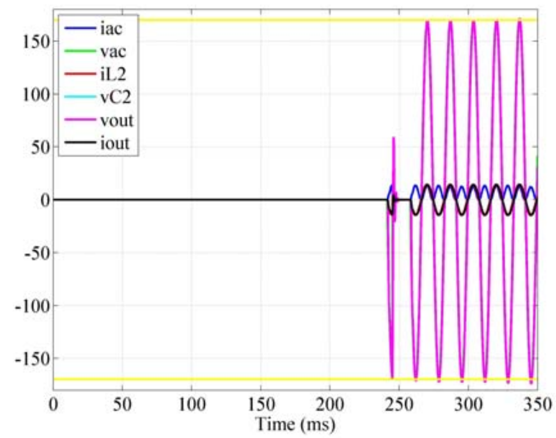


Figure 4. Example simulation results of the average value model. Inverter waveforms

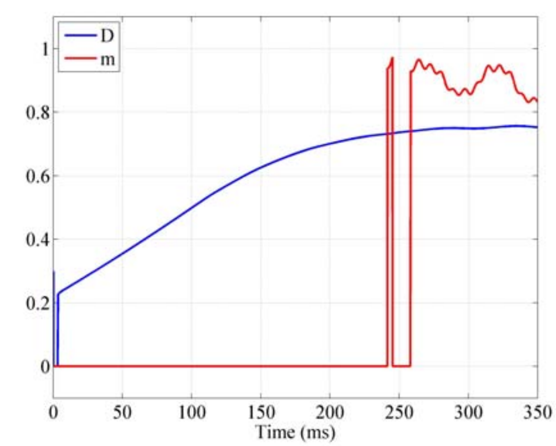


Figure 5. Example simulation results of the average value model. Controller waveforms

II. Duty Ratio

In the continuous mode of operation the duty ratio required to achieve a desired capacitor voltage v_{C1} for a given input voltage is defined as

$$D = 1 - \frac{v_{in}}{v_{C1}} . \tag{17}$$

Duty ratios equal to one are not achievable because of rise and fall times of switching events. To ensure that a valid range of operation is achievable the duty ratio is plotted, Figure 6, over the desired input voltage range for three values of v_{C1}.

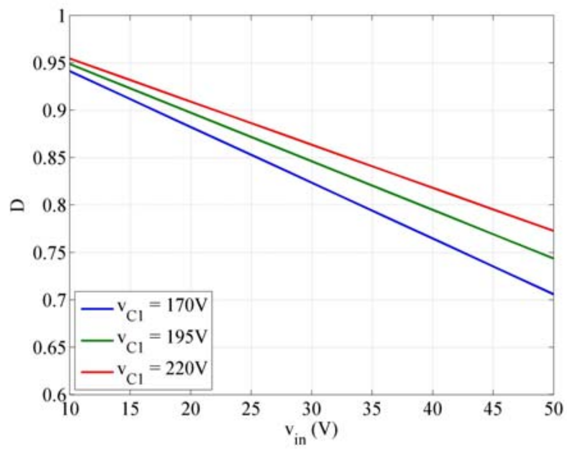


Figure 6. Duty ratio for several v_{C1} voltages.

III. Continuous Versus Discontinuous Operation

At the boundary between continuous and discontinuous operation the current i_{L1} reaches zero just at the time that SW_1 is turned on therefore satisfying the equation

$$\Delta i_{L1} = \frac{(v_{in} - i_{L1}R_1 - V_{SW1on})}{L_1}\Delta t_{on} = i_{L1pk} , \tag{18}$$

where Δi_{L1} is the change in current while SW_1 is on, V_{SW1on} is the voltage drop across SW_1 in the on state, and i_{L1pk} is the peak value of i_{L1} during a switching cycle. Since $\Delta i_{L1} = i_{L1pk}$ the boundary value current can be defined as

$$i_{L1B} = \frac{1}{2}\Delta i_{L1} . \tag{19}$$

Combining (18) and (19) and solving for L_1 results in

$$L_1 = \left(\frac{v_{in} - V_{SW1on}}{i_{L1B}} - R_1\right)\frac{D}{2 f_{sw}} , \tag{20}$$

which allows for an estimate for the required input inductance for a given duty ratio D, switching frequency f_{sw}, and boundary current i_{L1B}. The following three plots of this equation allow the inductance to be chosen based on input voltage, duty ratio, and input power. R_1, R_t, and V_{SW1on} are assumed to be zero for this analysis. Power is calculated as

$$P_{in} = \frac{v_{in}}{i_{L1B}} . \tag{21}$$

Figure 7 through Figure 9 use the same switching frequency f_{sw}, resistance R_1, and switch voltage V_{SW1on}. The difference between the three plots is the input voltage v_{in}. Values of 12V, 30V, and 48V were investigated.

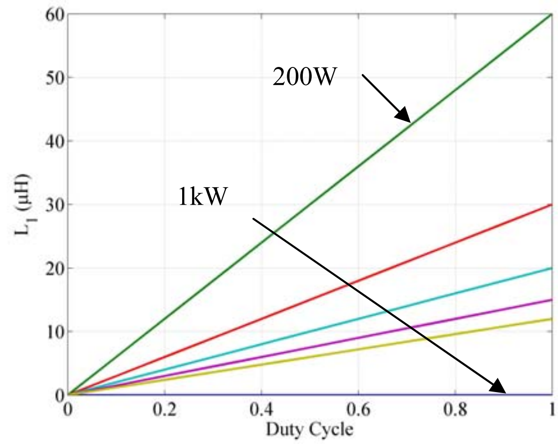


Figure 7. Input inductance vs duty ratio. (f_{sw} = 6kHz, v_{in} = 12V, R_1 = 0Ω, V_{SW1on} = 0V)

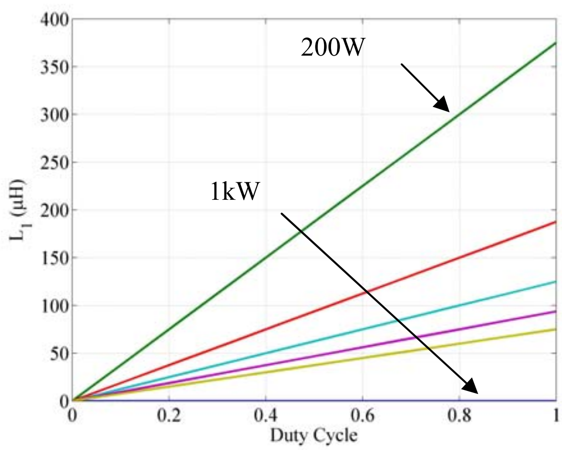


Figure 8. Input inductance vs duty ratio. (f_{sw} = 6kHz, v_{in} = 30V, R_1 = 0Ω, V_{SW1on} = 0V)

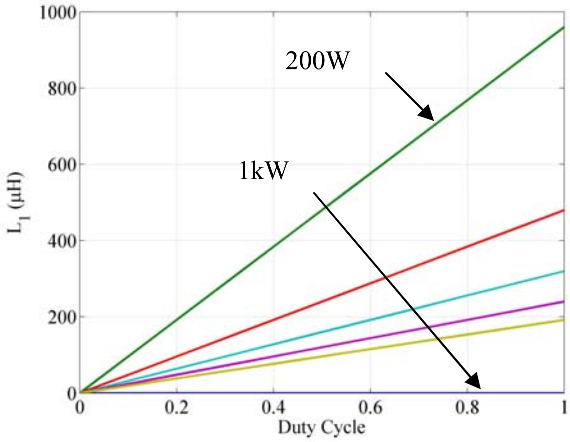


Figure 9. Input inductance vs duty ratio. (f_{sw} = 6kHz, v_{in} = 48V, R_1 = 0Ω, V_{SW1on} = 0V)

From Figure 7 through Figure 9 it can be seen that higher levels of input voltage require larger input inductances in order to stay in continuous operation. From Figure 9 an inductance value of 1mH will ensure that the boost converter will be in the continuous mode of operation for power levels greater than 200W and an input voltage of 48V.

Solving (20) for i_{L1B} results in

$$i_{L1B} = \frac{v_{in} - V_{SW1on}}{2 f_{sw} L_1 + DR_1} D , \tag{22}$$

which is used to generate Figure 10. In this figure as long as the current is greater than i_{L1B} for a given v_{in} and D the boost converter will be in the continuous mode of operation.

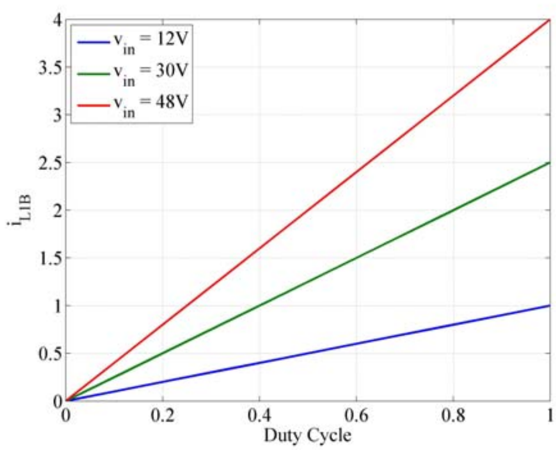


Figure 10. Estimated boundary current between continuous and discontinuous modes of operation. (f_{sw} = 6kHz, L_1 = 1.0mH, R_1 = 0Ω, V_{SW1on} = 0V)

IV. DC LINK VOLTAGE RIPPLE

The capacitance, C_1, necessary to keep the voltage ripple due to switching of the boost converter at a desired level can be calculated using

$$C_1 = \frac{P_{out} D}{\Delta v_{C1} v_{C1} f_{sw}} , \tag{23}$$

which assumes a constant current out of C_1. Values of C1 versus D are plotted below for a voltage ripple of 1%.

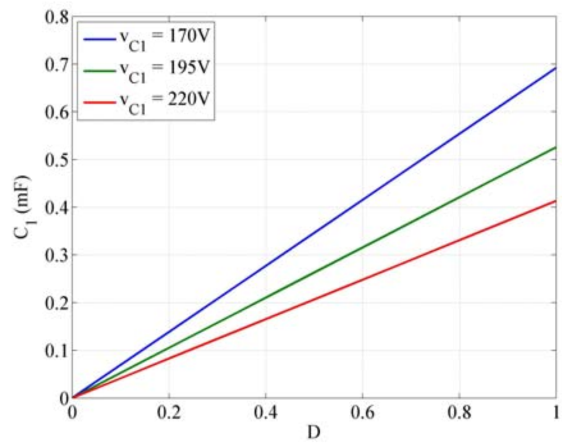


Figure 11. DC link capacitance needed for desired voltage ripple caused by boost converter switching. (f_{sw} = 6 kHz, P_{out} = 1.2 kW, Δv_{C1} = 1 % of v_{C1})

This capacitance value can also be considered in regards to how long the voltage will stay above a given level when the input power is lost. This time period provides some opportunity for the controller to react and bring the output down more gracefully. The voltage droop can be calculated as

$$v_{C1} = \sqrt{\frac{2E_s - 2P_{out} t}{C_1}} , \tag{24}$$

where

$$E_s = \frac{1}{2} C_1 v_{C1}{}^2 . \tag{25}$$

From Figure 12 it can be seen that a capacitance of 5 mF will provide about 15ms of operation before an initial voltage of 195 V drops below 170V mark and the inverter enters into a mode of over modulation if $N1N2$ is 1:1. Below this voltage additional harmonics will be introduced into the output waveform.

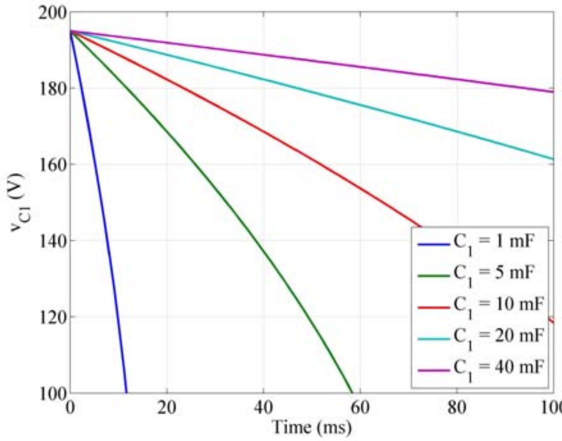


Figure 12. Voltage droop on C_1. (P_{in} = 0 kW, P_{out} = 1.2 kW)

V. Amplitude Modulation Ratio

The amplitude modulation ratio (from this point forward referred to as the modulation ratio)

$$m = \frac{V_{pk}}{v_{C1}}, \tag{26}$$

controls the peak value of the voltage out of the inverter as can be seen in (15). The turns ratio of the transformer must be considered when selecting V_{pk}. For this power supply the output voltage is required to be 120 Vrms therefore the peak value of the fundamental out of the inverter must be regulated to

$$V_{pk} = \frac{120\sqrt{2}}{N1N2}. \tag{27}$$

From Figure 13 choosing an isolation transformer with a 1:1 turns ratio will keep the modulation ratio below one as long as v_{C1} is greater than 170 V.

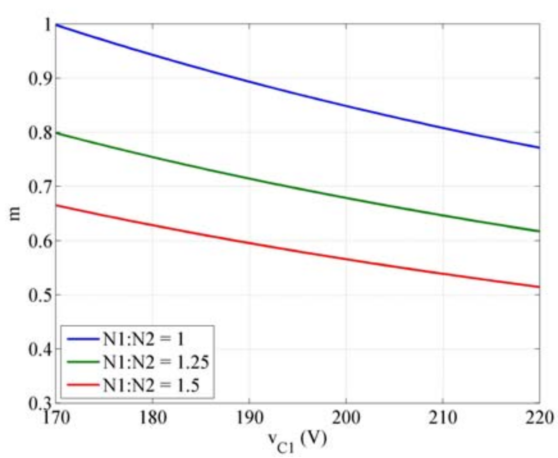


Figure 13. Modulation ratio for a few transformer turn ratios.

VI. Output Filter

The output filter cutoff frequency of 600Hz was chosen to be an order of magnitude less than the 6kHz switching frequency and an order of magnitude greater than the fundamental frequency 60Hz. This analysis neglects R_2 when calculating L_2 versus C_2.

$$L_2 = \frac{1}{C_2 \varpi_c^{\,2}}, \tag{28}$$

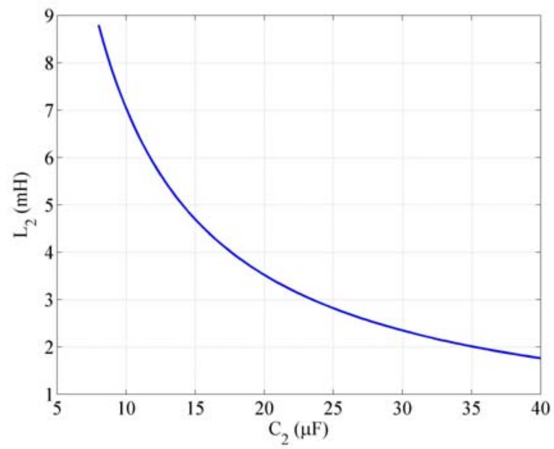


Figure 14. Estimated filter inductor for a given filter capacitor. (f_c = 600Hz, R_2 = 0Ω)

VII. Output Transformer

An output transformer is not required to achieve the required output voltage as can be observed by the modulation ratio calculations plotted in Figure 13. However, an isolation transformer will provide some protection to the power supply and allow the ground connections to be separated.

VIII. Boost Control

A place holder for the Boost control was put in the simulation. Stability and robustness over the entire operating range were not analyzed or tested. All signals into the controller are filtered with a double pole low pass filter f_c = 600Hz.

IX. Inverter Control

A place holder for the Inverter control was put in the simulation. Stability and robustness over the entire operating range were not analyzed or tested. All signals are filtered with a single pole low pass filter f_c = 600Hz.

X. Thermal Analysis

This analysis is based on the maximum average current flowing through each device. Power dissipated in a switch is estimated as

$$P_{SW} = \bar{i}_{SW} V_{SWcond} + \frac{1}{2} \bar{i}_{SW} \bar{v}_{SWopen} (t_r + t_f) f_{sw}, \quad (29)$$

where $\bar{i}_{SW}$ is the average current through the switch, V_{SWcond} is the conduction voltage drop across the switch, $\bar{v}_{SWopen}$ is the voltage across the switch while open, t_r is the rise time of the voltage across the switch when opening, t_f and is the fall time of the voltage across the switch when closing. A similar equation can be formulated for the diode. Equation (29) along steady state thermal circuit diagrams were used to estimate the junction temperature of each of the semiconductor devices. An analysis at full power for each three different input voltage levels was performed.

A. Boost converter with heat sink fan

The circuit diagram is provided in Figure 1 and includes blocks representing the controllers. With the heat sink fan on the boost inverter can run at full power at input voltages as low as 33 V if the ambient temperature is 30 °C. The thermal circuit for the boos converter is provided in Figure 15 and the parameters that were used in the evaluation are provided in Table IV. The heat sink temperature and semiconductor junction temperatures are plotted in Figure 16 and Figure 17. In Figure 17 it can be seen that under these conditions the diode junction temperature reaches 150 °C and the device will be at risk of damage. Therefore the diode is the limiting component.

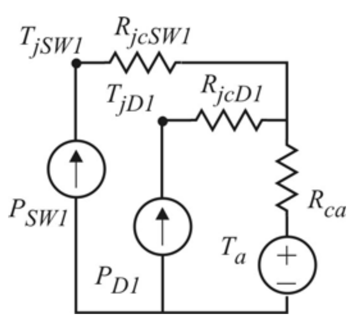


Figure 15. Circuit for thermal analysis.

Table IV. Boost converter thermal analysis parameters.

output power	P_{out}	1.2 kW
switching frequency	f_{sw}	6 kHz
input voltage	v_{in}	33 V [1]
DC link voltage	v_{C1}^*	195 V
Heatsink thermal resistance	R_{ca}	0.08 ºC/W
SW_1		
thermal resistance	R_{jc}	0.485 ºC/W
rise time	t_r	80 ns
fall time	t_f	250 ns
conduction voltage	V_{SWcond}	2.2 V
D_1		
thermal resistance	R_{jc}	0.955 ºC/W
rise time	t_r	150 ns
fall time	t_f	150 ns
conduction voltage	V_{SWcond}	2.6 V

[1] This is the minimum input voltage that this power supply can be operated from at full power and an ambient temperature of 30 °C.

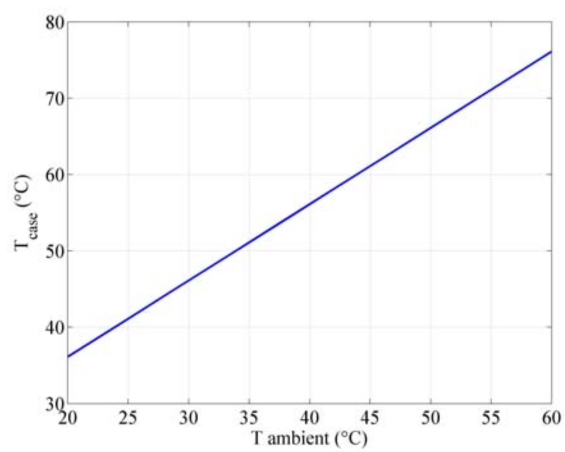


Figure 16. Estimated heat sink temperature.

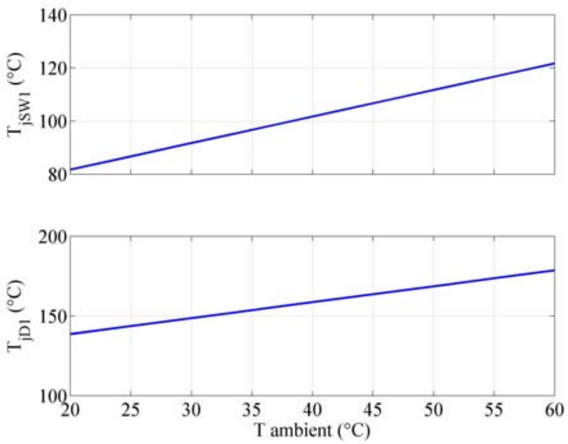


Figure 17. Estimated junction temperatures for SW_1 and D_1.

B. Boost converter without heat sink fan

The circuit diagram is provided in Figure 1 and includes blocks representing the controllers. With the heat sink fan on the boost inverter can run at full power at input voltages as low as 46 V if the ambient temperature is 30 °C. The thermal circuit for the boost converter is provided in Figure 15 and the parameters that were used in the evaluation are provided in Table V. The heat sink temperature and semiconductor junction temperatures are plotted in Figure 18 and Figure 19. In Figure 19 it can be seen that under these conditions the diode junction temperature reaches 150 °C and the device will be at risk of damage. Therefore the diode is the limiting component.

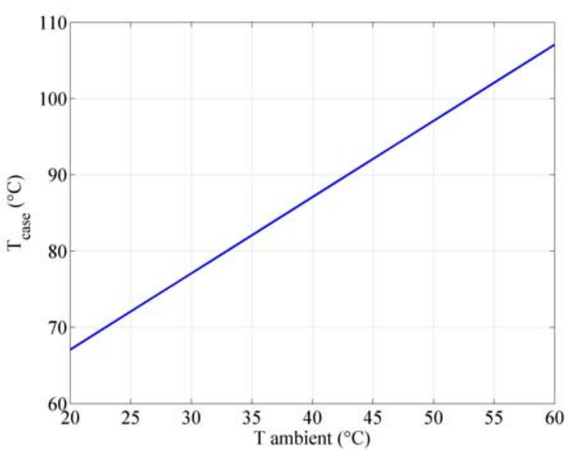


Figure 18. Estimated heat sink temperature.

Table V. Boost converter thermal analysis parameters.

output power	P_{out}	1.2 kW
switching frequency	f_{sw}	6 kHz
input voltage	v_{in}	46 V [1]
DC link voltage	v_{C1}^{*}	195 V
Heat sink thermal resistance (estimated)	R_{ca}	0.22 ºC/W [2]
SW_1		
thermal resistance	R_{jc}	0.485 ºC/W
rise time	t_r	80 ns
fall time	t_f	250 ns
conduction voltage	V_{SWcond}	2.2 V
D_1		
thermal resistance	R_{jc}	0.955 ºC/W
rise time	t_r	150 ns
fall time	t_f	150 ns
conduction voltage	V_{SWcond}	2.6 V

[1] This is the minimum input voltage that this power supply can be operated from at full power and an ambient temperature of 30 °C.

[2] This thermal resistance is an estimated value based on scaling the size from other natural convection heat sinks.

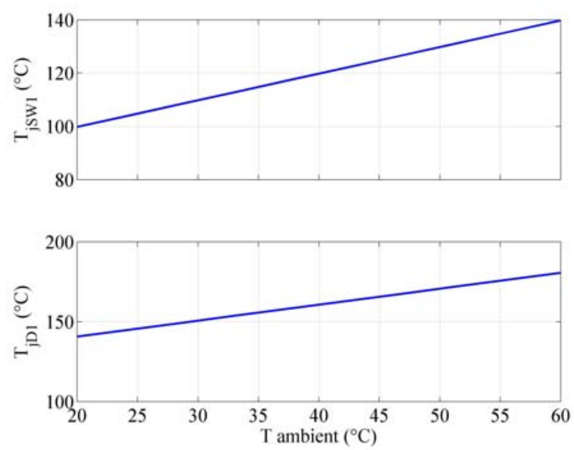


Figure 19. Estimated junction temperatures for SW_1 and D_1.

C. Inverter

The thermal performance of the inverter is independent of the MMI input voltage but will be somewhat dependent upon the DC link voltage. The thermal circuit for the H-bridge is provided in Figure 20 and the parameters that were used in the evaluation are provided in Table VI. The heat sink temperature and semiconductor junction temperatures are plotted in Figure 21, Figure 22 and Figure 23. In Figure 22 and Figure 23 switch junction temperatures do not reach 150 °C even at ambient temperatures as high as 60 °C. Therefore the boost converter will reach thermal limitations prior to the inverter reaching thermal limitations.

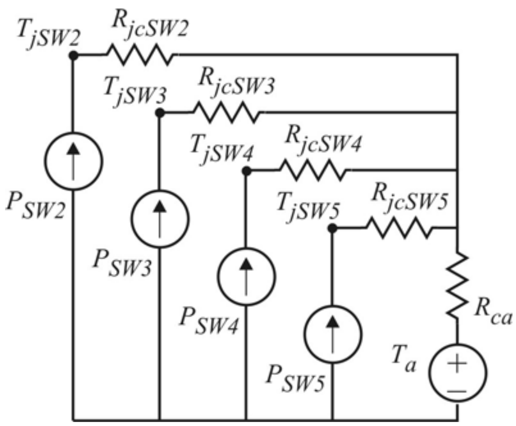


Figure 20. Circuit for thermal analysis.

Table VI. Inverter thermal analysis parameters.

output power	P_{out}	1.2 kW
switching frequency	f_{sw}	6 kHz
input voltage	v_{in}	48 V
DC link voltage	v_{C1}^{*}	195 V
Heat sink thermal resistance (estimated)	R_{ca}	0.22 ºC/W [1]
SW_2, SW_3, SW_4, SW_5		
thermal resistance	R_{jc}	0.485 ºC/W
rise time	t_r	80 ns
fall time	t_f	250 ns
conduction voltage	V_{SWcond}	2.2 V

[1] This thermal resistance is an estimated value based on scaling the size from other natural convection heat sinks.

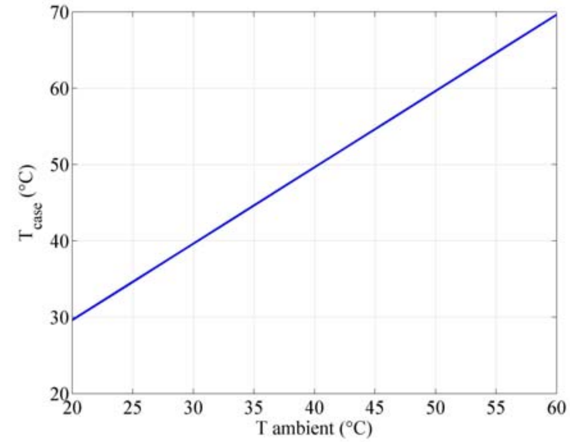


Figure 21. Estimated heat sink temperature for SW_2 through SW_5.

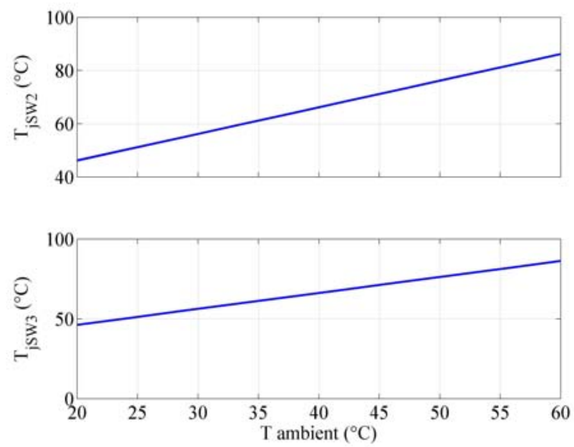


Figure 22. Estimated junction temperatures for SW_2 and SW_3.

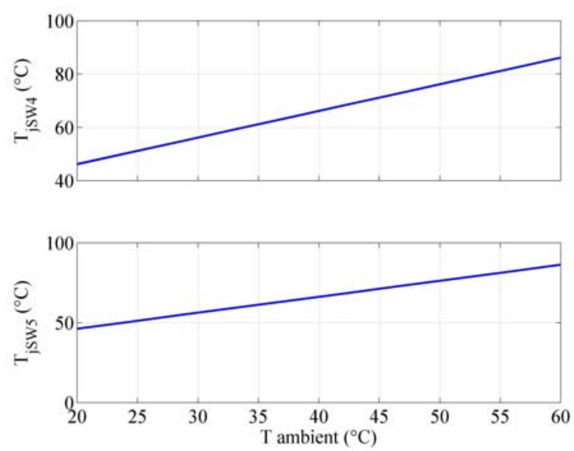


Figure 23. Estimated junction temperatures for SW_4 and SW_5.

XI. COMPONENT BASED POWER DERATING

Operational limitations of the MMI need to be limited to the operating range of the components within the MMI. Note that the MMI can operate over a large range of input voltages. However, the input current range is limited to a maximum of 25 Adc by the design of the boost inductor L_1 and 10 Arms by the design of the filter inductors L_{2a} and L_{2b}. Since the output of the MMI is regulated to be a 120 Vrms sinusoid the maximum output power is 1.2 kW. However, in order to ensure that L_1 is operating within the designed current limitations the input of the MMI must be derated as the input voltage decreases. Figure 24 contains a plot of the power versus input voltage. Note that for input voltages greater than 48 V the input power is still limited to 1.2 kW but the limiting components become the filter inductors L_{2a} and L_{2b} at the MMI output.

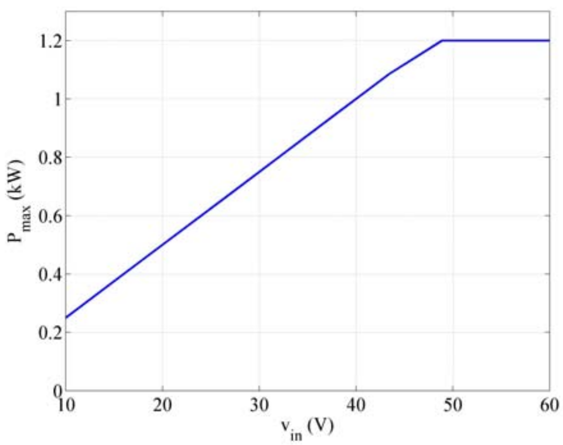


Figure 24. Maximum input power versus input voltage.

XII. CONDUCTION BASED POWER DERATING

Due to the low input voltage, the saturation voltage V_{SWcond} across SW_1, and the resistance R_1 there is a maximum input power for a given input voltage. Note that any resistance or voltage drops external to the MMI (for example internal to the solar panel) will affect this limitation as well but are not being included in these calculations. Based on these parameters the maximum input current is

$$i_{L1\max} = \frac{v_{in} - V_{SWcond}}{R_1}, \tag{30}$$

which can be used to estimate the maximum input power

$$P_{\max} = v_{in} i_{L1\max}. \tag{31}$$

Using these equations $i_{L1\max}$ and $P_{\max}$ are plotted in Figure 25 and Figure 26 with V_{SWcond} =2.8 V. In Figure 26 it is shown that for an input resistance R_1 > 0.1 Ω the desired power of 1 kW is only achievable for input voltages greater than 12 V. For voltages less than this the power supply will need to be derated. Note that the input resistance due to the inductance L_1 is expected to be less than 15 m Ω.

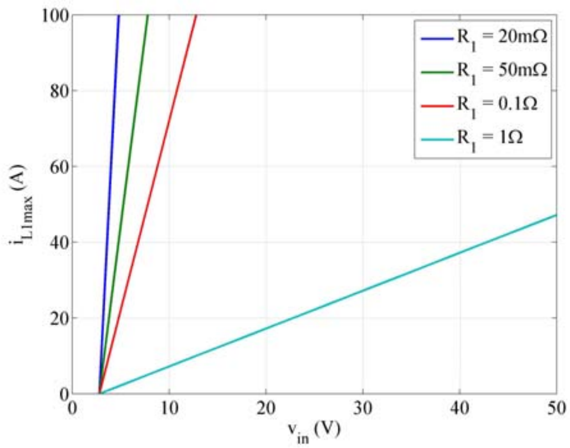


Figure 25. Maximum input current, limited by voltage drops and resistances.

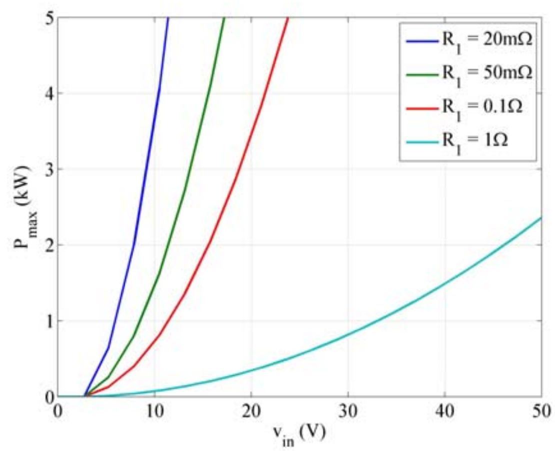


Figure 26. Maximum input power, limited by voltage drops and resistances.

XIII. SENSOR SIGNAL FILTERS

All sensor signals with bandwidths greater than 600Hz are filtered with a 600 Hz second order low pass Butterworth filter. The circuit diagram and the layout are provided in Figure 27 and Figure 28 below.

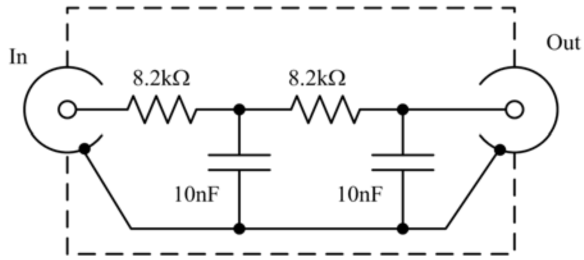


Figure 27. Signal filter.

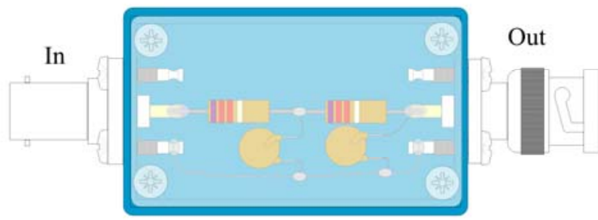


Figure 28. Signal filter layout.

XIV. INPUTS AND OUTPUTS

Table VII. Power Connections

1		DC input 0 V – 250 V, 25 A max
2		AC output 0 V rms – 120 Vrms, 10 A max
3		120 V AC power source for controls, 5 A

Table VIII. Sensor and fault signals

1	v_{in}	Input Voltage, filtered at 600 Hz, BNC
2	i_{L1}	Current through inductor L_1, filtered at 600 Hz, BNC
3	v_{C1}	Voltage across C_1, filtered at 600 Hz, BNC
4	i_{L2}	Current through inductor L_2, filtered at 600 Hz, BNC
5	v_{C2}	Voltage across C_2, filtered at 600 Hz, BNC
6	v_{out}	Voltage across the contactor, Con_1, output, filtered at 600 Hz, BNC
7	i_{out}	Current out of MMI, filtered at 600 Hz, BNC
8		Boost converter thermal switch, BNC
9		SW1 over current, fiber
10		Bridge fault, fiber
11		Bridge leg A over current, fiber
12		Bridge leg B over current, fiber

Table IX. Control signals

1	G_{SW1}	Gate signal for SW_1, fiber
2	G_{SW2}	Gate signal for SW_2, fiber
3	G_{SW3}	Gate signal for SW_3, fiber
4	G_{SW4}	Gate signal for SW_4, fiber
5	G_{SW5}	Gate signal for SW_5, fiber
6		Contactor, BNC

XV. PHOTOGRAPHS OF THE MMI

Figure 29. MMI enclosure with ruler..

Figure 30. MMI DC input side

Figure 31. MMI AC output side

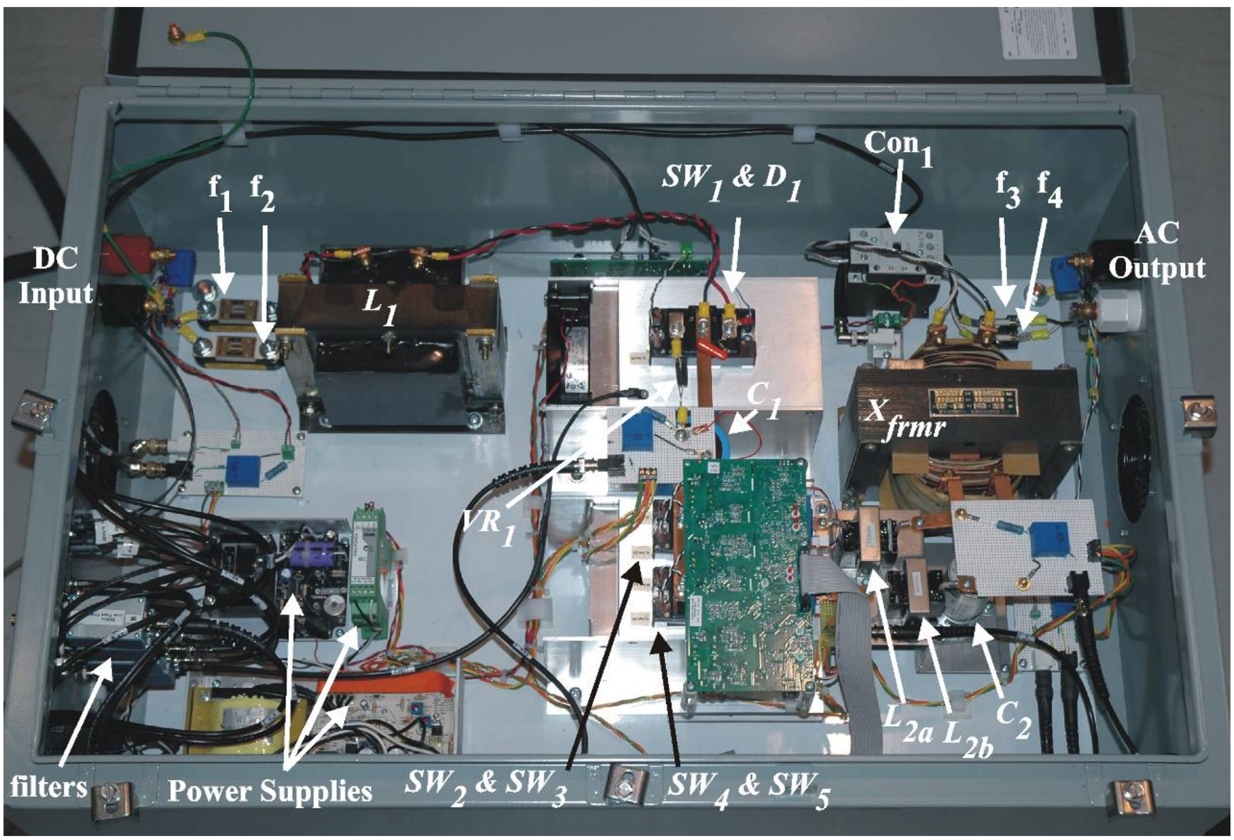


Figure 32. MMI interior

Figure 33. Picture of the signal inputs and outputs

XVI. References

[1] N. Mohan, T.M. Undeland, W.P. Robbins, "Power Electronics: Converters, Applications, and Design," John Wiley & Sons, Inc., 1995.

[2] MATLAB The Language of Technical Computing, The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098 USA, info@mathworks.com.

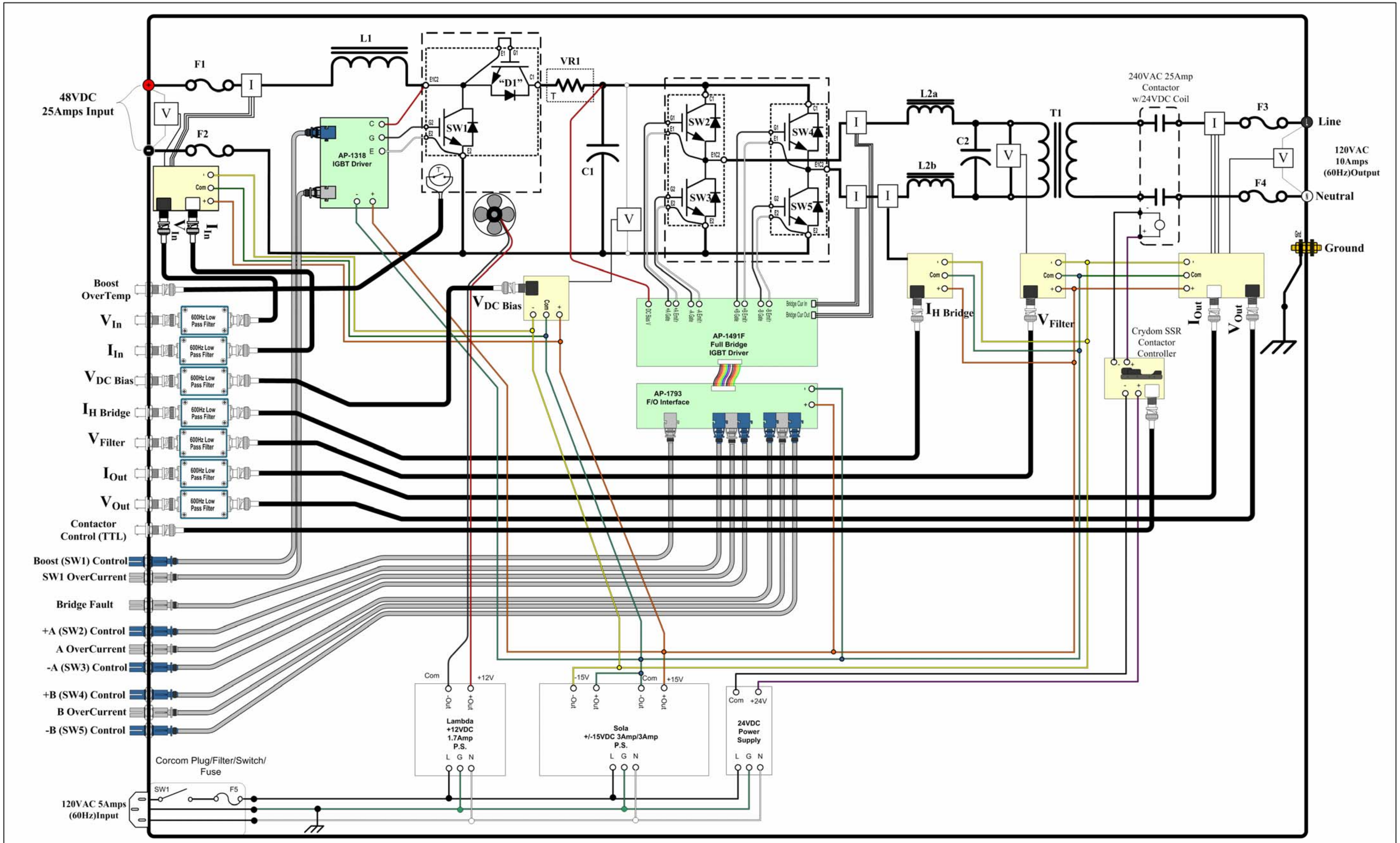
[3] Jim Puissant, Ktech, (505) 845-7383, jgpuiss@sandia.gov.

XVII. Appendix - Parts List

Item	Symbol	Tech. Specs.	Quantity	Maufac.	Maufac Part#	Vendor	Vendor Part#	Part Quantity	Unit Cost	Extended Cost	Date Ordered	Ordered by:	Type Order/(PO# if applies)	Quan.	Date Recv'd	Delivery Time (days)	Quan.	Date Recv'd	Delivery Time (days)
1	L1	1.0 mH, 25A, 250V, 10kHz	3	L/C Magnetics	5275L4d (9" x 9" x 9")	L/C Magnetics	5275L4d	3	$1,552.00	$4,656.00	7/28/2008	Christina	P-Card						
2	L2a,L2b	1.0 mH, 25A, 250V, 10kHz	6	L/C Magnetics	5275L1Bb (4" x 4" x 4")	L/C Magnetics	5275L1Bb	6	$795.00	$4,770.00	7/28/2008	Christina	P-Card						
3	C1	5.2 mF, 250A, 250V, Ω ESR	3	Cornell-Dubilier	CGS422T250W5L (4.2mF, 250WVDC)	Newark	69K1868	3	$60.40	$181.20	7/31/2008	Christina	P-Card	3	8/4/2008	4			
4	C2	36 uF, 25A, 250V, Ω ESR	3	Cornell-Dubilier	SFC37S35K291B (35uF, 370WVDC)	Newark	66K4139	3	$37.17	$111.51	7/31/2008	Christina	P-Card	3	8/4/2008	4			
5	D1	Fast Recovery Power Diode, 250A, 250V, 10kHz, Rth j-c = XX °C/W, Rth c-a = XX °C/W	0					0		$0.00									
6	SW1	Fast Recovery Dual IGBT, 25A, 250V, 10kHz, Rth j-c = XX °C/W, Rth c-a = XX °C/W	3	Powerex	CM75DU-12F (Dual 75A,600V)	Richardson Electronics	CM75DU-12F	3	$50.57	$151.71	7/31/2008	Christina	P-Card						
7	SW2,SW3	Fast Recovery Dual IGBT, 25A, 250V, 10kHz, Rth j-c = XX °C/W, Rth c-a = XX °C/W	3	Powerex	CM75DU-12F (Dual 75A,600V)	Richardson Electronics	CM75DU-12F	3	$50.57	$151.71	7/31/2008	Christina	P-Card						
8	SW4,SW5	Fast Recovery Dual IGBT, 25A, 250V, 10kHz, Rth j-c = XX °C/W, Rth c-a = XX °C/W	3	Powerex	CM75DU-12F (Dual 75A,600V)	Richardson Electronics	CM75DU-12F	3	$50.57	$151.71	7/31/2008	Christina	P-Card						
9	Xfrmr	Isolation transformer, 1.2kVA, 60Hz, N1:N2 = 1:1, 300V isolation	3	L/C Magnetics	5275L3c (7.5" x 7.5" x 7.5")	L/C Magnetics	5275L3c	3	$575.00	$1,725.00	7/28/2008	Christina	P-Card						
10	Enclosure		3	Hammond	Steel 1418N4L12 (36"x24"x12")	Allied Electronics	8061061	3	$576.19	$1,728.57	7/31/2008	Amy	P-Card	1	8/1/2008	1	2	8/8/2008	8
11	Fans	4.72"x1.54", 12VDC/0.5A, 110CFM	0	COMAIR-ROTRON	MD12B2 028868	Allied Electronics	599-0288	3	$49.58	$148.74	7/31/2008	Amy	P-Card	3	8/4/2008	4			
12	Vent Screens	4.72" 'Finger Guards'	12	COMAIR-ROTRON	550481 (4.72" -Zinc plated steel wire)	Allied Electronics	599-5504	12	$1.16	$13.92	7/31/2008	Amy	P-Card						
13	Heat sink #1		3	Aavid Thermalloy	476200U00000	Electronics Precepts	476200U00000	3	$132.90	$398.70	7/29/2008	Christina	P-Card	3	8/4/2008	6			
14	Heat sink #2		3	Aavid Thermalloy	476200U00000	Electronics Precepts	476200U00000	3	$132.90	$398.70	7/29/2008	Christina	P-Card	3	8/4/2008	6			
15	V_{C1} sensor	0-250V, 0-600Hz	3	Sandia	Vc1	Sandia	Vc1												
16				Sypris-F.W. Bell	CLSM-10MA	Allied Electronics	595-0004	3	$30.16	$90.48	7/31/2008	Amy	P-Card						
17	Rv2	30kΩ, 5W,1% wirewound Resister	3	Ohmite	45F30KE	Allied Electronics	296-5556	12	$2.56	$30.72	7/31/2008	Amy	P-Card	12	8/4/2008	4			
18	Rm2	400Ω, 1/2W, 1% metal film	3	Phoenix Passive Components	MRS25 402R 1%	Newark	97K5808	100	$0.04	$3.50	7/31/2008	Christina	P-Card	100	8/6/2008	6			
19										$0.00									
20										$0.00									
21	i_{L2} Sensor	±10A, 0-600Hz	3	Sypris-F.W. Bell	CLS-25	Allied Electronics	595-0029	3	$24.27	$72.81	7/31/2008	Amy	P-Card	3	8/4/2008	4			
22	Rm3	400Ω, 1/2W, 1% metal film	3	Phoenix Passive Components	MRS25 402R 1%	Newark	97K5808	see item 18											
23	V_{C2} Sensor	±190V, 0-600Hz	3	Sandia	Vc2	Sandia	Vc2												
24				Sypris-F.W. Bell	CLSM-10MA	Allied Electronics	595-0005	3	$30.16	$90.48	7/31/2008	Amy	P-Card						
25	Rv6	15kΩ, 5W,1% wirewound Resister	3	Ohmite	45F15KE	Allied Electronics	296-5527	12	$2.09	$25.08	7/31/2008	Amy	P-Card	12	8/4/2008	4			
26	Rm6	316Ω, 1/2W, 1% metal film	3	Phoenix Passive Components	MRS25 316R 1%	Newark	97K5739	100	$0.04	$3.50	7/31/2008	Christina	P-Card	100	8/6/2008	6			
27		360ohm, 1/2 W,1% metal film	3	Phoenix Passive Components	MRS25360R 1%	Newark	78K5739	100	$0.04	$4.00	8/7/2008	Christina	P-Card						
28										$0.00									
29	thermal sensor		3	Honeywell	573T110A120	Border States	573T110A120	6	$35.00	$210.00									
30	SW1 Gate driver		3	Applied Power Systems Inc.	AP-1318	Applied Power Systems Inc.	AP-1318	3	$256.00	$768.00	7/30/2008	Amy	P-Card						
31	Analog connection		3	Sandia	"IPC Control Interface Assy with signal filtering"			0		$0.00									
32	Internal power supply	"+/- 15VDC (3Amps),"	3	Sola/Heavy Duty	SLD15-3030-15T	Newark	93K6593	3	$121.89	$365.67	7/31/2008	Christina	P-Card	3	8/4/2008	4			
33	Internal power supply	Fan Power Supply - +12VDC (1.7Amps)	3	Sola/Heavy Duty	HSB-12-1.7	Newark	14M5851	3	$41.51	$124.53	7/31/2008	Christina	P-Card	3	8/4/2008	4			
34	SW2,3,4,5 Gate Driver		3	Applied Power Systems Inc.	AP-1491F, Full Bridge IGBT Driver	Applied Power Systems Inc.	AP-1491F	3	$389.00	$1,167.00	7/30/2008	Amy	P-Card						
35	F/O Interface For Above		3	Applied Power Systems Inc.	AP-1793, IGBT Driver Interface	Applied Power Systems Inc.	AP-1793	3	$305.00	$915.00	7/30/2008	Amy	P-Card						
36	Fuse		6	Cooper-Bussman	ANL-35 ro ANL-40	Newark	02B2084 or 02B2086	6	$35.00	$210.00	7/31/2008	Christina	P-Card	5	8/7/2008	7	1	8/8/2008	8
37	Fuse Holder		6	Cooper-Bussman	Fuseblock 4164	Newark	94F2259	6	$35.00	$210.00	7/31/2008	Christina	P-Card	6	8/4/2008	4			
38	`	Negative temperature coefficient thermistor 2 Ohm	3	AMETHERM	SL22 2R018	Newark	72J6826	12	$1.80	$21.60	7/31/2008	Christina	P-Card	12	8/4/2008	4			
39	FO	Capacitor Mounting bracket 2.5in.-2.56in.dia.	3	CDE	VR10A	Newark	60D2292	3	$2.62	$7.86	8/5/2008	Christina	P-Card	3	8/8/2008	2			
40	FO	Capacitor Mounting bracket 1.75in.-1.81in.dia.	3	CDE	VR6A	Newark	14F412	3	$2.59	$7.77	8/5/2008	Christina	P-Card	3	8/8/2008	2			
41	FO	Fiber Optic Cable Simplex POF 10 meters	2	Avago	HFBR-RNS010Z	Newark	71K0250	2	$14.74	$29.48	8/5/2008	Christina	P-Card	2	8/8/2008	2			
42	FO	Fiber Optic Cable Duplex F 10 meters	2	Avago	HFBR-RMD010Z	Newark	71K0247	2	$29.47	$58.94	8/5/2008	Christina	P-Card						
43	FO	Fiber Optic Connector, Gray	50	Avago	HFBR-4501Z	Newark	74K5180	50	$0.56	$28.20	8/5/2008	Christina	P-Card	50	8/8/2008	2			
44	FO	Fiber Optic Connector, Blue	50	Avago	HFBR-4511Z	Newark	74K5184	50	$0.56	$27.78	8/5/2008	Christina	P-Card	50	8/8/2008	2			
45	FO	Fiber Optic Adapter, Gray	20	Avago	HFBR-4505Z	Newark	74K5182	20	$1.04	$20.80	8/5/2008	Christina	P-Card	20	8/8/2008	2			
46	FO	Fiber Optic Adapter, Blue	20	Avago	HFBR-4515Z	Newark	74K5186	20	$1.04	$20.80	8/5/2008	Christina	P-Card	20	8/5/2008	2			
47	FO	Polishing Kit	6	Avago	HFBR-4593Z	Newark	74K5195	6	$4.19	$25.14	8/5/2008	Christina	P-Card	6	8/8/2008	2			
48	FO	Fiber Optics Receiver	10	Avago	HFBR-2524Z	Newark	71K0283	10	$7.92	$79.20	8/52008	Christina	P-Card	10	8/8/2008	2			
49	FO	Fiber Optic Emitter	10	Avago	HFBR-1524Z	Newark	71K0266	10	$7.92	$79.20	8/5/2008	Christina	P-Card	10	8/8/2008	2			
50	DC IN,PWR OUT	Red Supercon 100amp Connector	6	Superior Electric	RP100GR Red	Walker Electronics	RP100GR Red	6	$38.80	$232.80	8/6/2008	Christina	P-Card	6	8/10/2008	2			
51	DC IN,PWR OUT	BlackSupercon 100amp Connector	6	Superior Electric	RP100GB Black	Walker Electronics	RP100GB lack	6	$38.80	$232.80	8/6/2008	Christina	P-Card	6	8/10/2008	2			
52	DC IN,PWR OUT	Red Supercon 100amp Plug	1	Superior Electric	PS100GR Red	Walker Electronics	PS100GR Red	1	$38.80	$38.80	8/6/2008	Christina	P-Card	1	8/10/2008	2			
53	DC IN,PWR OUT	Black Supercon 100amp Plug	1	Superior Electric	PS100GB Black	Walker Electronics	PS100GB Black	1	$38.80	$38.80	8/6/2008	Christina	P-Card	1	8/10/2008	2			
54	Fan Guard/Filter	Cabinet Fan & Filter	7	Newark	90F1255	Team Technologies	09450F/30	7	$2.89	$20.23	9/29/2008	Mike H.	P-Card	7	10/30/2008	30			
55	Temp. Monitor	Thermostat	5	Digikey	317-1002-ND	Team Technologies	317-1002-ND	5	$8.20	$41.00	10/8/2008	Mike H.	P-Card	5	10/13/2008	5			
56	Temp. Monitor	Thermostat	5	Digikey	317-1004-ND	Team Technologies	317-1004-ND	5	$8.20	$41.00	10/8/2008	Mike H.	P-Card	5	10/13/2008	5			
57	Temp. Monitor	Thermostat	5	Digikey	317-1021-ND	Team Technologies	317-1021-ND	5	$10.65	$53.25	10/8/2008	Mike H.	P-Card	5	10/13/2008	5			
58	Temp. Monitor	Thermostat	5	Digikey	317-1023-ND	Team Technologies	317-1023-ND	5	$10.65	$53.25	10/8/2008	Mike H.	P-Card	5	10/13/2008	5			
59	Ribbon Connector	Ribbon Connector parts	4	Newark	46F4669	Team Technologies	46F4669	4	$0.27	$1.08	11/10/2008	Mike H.	P-Card	4	12/5/2008	25			
60	Ribbon Connector	Ribbon Connector parts	4	Newark	90F1456	Team Technologies	90F1456	4	$4.23	$16.92	11/10/2008	Mike H.	P-Card	4	12/5/2008	25			
61	Ribbon Connector	Ribbon Connector parts	15	Newark	45J3195	Team Technologies	45J3195	15	$0.27	$4.05	11/10/2008	Mike H.	P-Card	15	12/5/2008	25			
62	Temp. Monitor	Temperature sensor	4	Newark	41K4845	Team Technologies	LM35CZ/NOPB	4	$3.35	$13.40	11/10/2008	Mike H.	P-Card	4	11/18/2008	8			
63	Temp. Monitor	Temperature sensor	4	Newark	92F286	Team Technologies	LM35CAZ	4	$3.86	$15.44	11/10/2008	Mike H.	P-Card	4	11/18/2008	8			
64	Ribbon Cable	Ribbon Cable Asmbly, 3M 26pin,I/O,1DC/1DT	5	Team Technologies	TM3365/12-1.5	Team Technologies	TM3365/12-1.5	5	$13.11	$65.57	11/17/2008	Mike H.	P-Card	5	12/5/2008	20			
68	Power Out	White Supercon 100amp Connector	6	Superior Electric	RP100GW White	Walker Electronics	RP100GW White	6	$34.50	$207.00	11/20/2008	Christina	P-Card						
69	Power Out	Black Supercon 100amp Connector	2	Superior Electric	RP100GB Black	Walker Electronics	RP100GB Black	2	$34.50	$69.00	11/20/2008	Christina	P-Card						
70	Power Out	White Supercon 100amp Plug	1	Superior Electric	PS100GW White	Walker Electronics	PS100GW White	1	$34.50	$34.50	11/20/2008	Christina	P-Card						
71	Current Monitor	Closed Loop Current Transducers	10	LEM	LAH 100-P	Digikey	398-1009-ND	10	$26.40	$264.00	11/26/2008	Christina	P-Card	10	12/8/2008	12			
72	Voltage Monitor	Closed Loop Voltage Transducers	15	LEM	LV 25-P	Digikey	398-1019-ND	15	$50.56	$758.40	11/26/2008	Christina	P-Card	15	12/8/2008	12			
73	Amp/Volt Monitors	SL Crimp Female Terminals, 24-22 awg.	150	Waldom/molex	16-02-0102	Allied Electronics	863-0369	150	$0.06	$9.00	12/8/2008	Christina	P-Card	150	12/11/2008	3			
74	Amp/Volt Monitors	SL Single Row Crimp Conn.Housing, 3 circuit	30	Waldom/molex	50-57-9003	Allied Electronics	863-0254	30	$0.29	$8.70	12/8/2008	Christina	P-Card	30	12/11/2008	3			
75	Amp/Volt Monitors	Ceramic coated COG (NPO) 1000pf, 200V	50	KEMET	C330C103J2G5TA	Allied Electronics	541-0176	50	$0.73	$36.50	12/8/2008	Christina	P-Card	50	12/11/2008	3			
76	Amp/Volt Monitors	GP55 1/4W Resistor, metal film, 348ohm	100	R C D	GP55-3480-FTW	Allied Electronics	840-0392	100	$0.01	$1.00	12/8/2008	Christina	P-Card	100	12/11/2008	3			
77	Amp/Volt Monitors	OK Ser. 1/4W Resistor, carbon film,8.2kohm	100	OHMITE	OK8225E	Allied Electronics	296-6598	100	$0.03	$3.00	12/8/2008	Christina	P-Card	100	12/11/2008	3			
78	Amp/Volt Monitors	Alum.Enclosure w/BNC Female In/Out	20	Pomona	3230	Allied Electronics	885-3230	20	$23.95	$479.00	12/8/2008	Christina	P-Card	20	12/11/2008	3			
79	Amp/Volt Monitors	40 Ser. Ohmicone Resistor, 5W, 25kohm	25	OHMITE	45F25KE	Allied Electronics	296-5549	25	$2.46	$61.50	12/8/2008	Christina	P-Card	25	12/11/2008	3			
80	Amp/Volt Monitors	Standoff, Alum. 6-32X .5in. Hex	40	Keystone	8414	Allied Electronics	839-0872	40	$0.35	$14.00	12/8/2008	Christina	P-Card	40	12/11/2008	3			
81	Amp/Volt Monitors	Standoff, Alum. 6-32X .75in. Hex	40	Keystone	8416	Allied Electronics	839-0874	40	$0.46	$18.40	12/8/2008	Christina	P-Card	40	12/11/2008	3			
82	Amp/Volt Monitors	Standoff, Alum. 6-32X 1in. Hex	40	Keystone	8418	Allied Electronics	839-0875	40	$0.50	$20.00	12/8/2008	Christina	P-Card	40	12/11/2008	3			
83	Amp/Volt Monitors	Standoff, Alum. 8-32X .5in. Hex	60	Keystone	8427	Allied Electronics	839-0881	60	$0.49	$29.40	12/8/2008	Christina	P-Card	60	12/11/2008	3			
84	Amp/Volt Monitors	Standoff, Alum. 8-32X .75in. Hex	60	Keystone	8429	Allied Electronics	839-0990	60	$0.53	$31.80	12/8/2008	Christina	P-Card	60	12/11/2008	3			
85	Amp/Volt Monitors	Standoff, Alum. 8-32X 1in. Hex	60	Keystone	8431	Allied Electronics	839-0883	60	$0.66	$39.60	12/8/2008	Christina	P-Card	60	12/11/2008	3			
86	Amp/Volt Monitors	OK Ser. 1/4W Resistor, carbon film, 100ohm	100	OHMITE	OK1015E	Allied Electronics	296-6638	100	$0.03	$3.00	12/8/2008	Christina	P-Card	100	12/11/2008	3			
87	Amp/Volt Monitors	OK Ser. 1/4W Resistor, carbon film, 120ohm	100	OHMITE	OK1215E	Allied Electronics	296-6639	100	$0.03	$3.00	12/8/2008	Christina	P-Card	100	12/11/2008	3			
88	Amp/Volt Monitors	40 Ser. Ohmicone Resistor, 5W, 10kohm	25	OHMITE	45F10KE	Allied Electronics	296-5523	25	$2.00	$50.00	12/8/2008	Christina	P-Card	25	12/11/2008	3			
89	Amp/Volt Monitors	Contactor, 3-Pole, 24VDC	3	Cutler-Hammer	XTCE025C10TD	Allied Electronics	416-0021	3	$208.08	$624.24	12/10/2008	Christina	P-Card	2p	12/16/2008	6	1	1/12/2009	28
90	Amp/Volt Monitors	Mini Pwr. Supply, 85-264VAC In, 24VDC Out	3	Phoenix Contact	2866446	Allied Electronics	209-0029	3	$103.02	$309.06	12/10/2008	Christina	P-Card	3	12/16/2008	6			
91	Amp/Volt Monitors	DMO Solid State relay, 0-60VDC, 0-3ADC	6	Crydom	DMO063	Allied Electronics	682-2374	6	$15.79	$94.74	12/10/2008	Christina	P-Card	6	12/16/2008	6			
92	Amp/Volt Monitors	Switching Relay, 0-60VDC, 0-5ADC	3	Crydom	CMX60D5	Allied Electronics	682-4078	3	$29.86	$89.58	12/10/2008	Christina	P-Card	3	12/16/2008	6			
93	Amp/Volt Monitors	Alum.Enclosure w/BNC Male in, Female out	20	Pomona	3231	Allied Electronics	885-3231	20	$29.34	$586.80	1/14/2009	Christina							
94																			
95	Amp/Volt Monitors	CoaxCableAsmbly,RG223,BNCmale-female,12in.	10	Pasternack	PE 3087-12	Pasternack Elect.	PE 3087-12	10	$21.20	$212.00	1/14/2009	Christina							
96	Amp/Volt Monitors	CoaxCableAsmbly,RG223,BNCmale-female,24in.	10	Pasternack	PE 3087-24	Pasternack Elect.	PE 3087-24	10	$22.20	$222.00	1/14/2009	Christina							
97	Amp/Volt Monitors	CoaxCableAsmbly,RG223,BNCmale-female,36in.	6	Pasternack	PE 3087-36	Pasternack Elect.	PE 3087-36	6	$23.10	$138.60	1/14/2009	Christina							
98	Amp/Volt Monitors	CoaxCableAsmbly,RG223,BNCmale-female,60in.	10	Pasternack	PE 3087-60	Pasternack Elect.	PE 3087-60	10	$25.10	$251.00	1/14/2009	Christina							
99																			
100		misc supplies	3					3	$79.00	$237.00									
									Total Cost =>	$25,059.21									
									Cost/MMI=>	$8,353.07									

Inductors were potted with epoxy [3]. Manufacturer:Crosslink Technologies, 6380 Viscount Road, Mississauga, ON L4V1H3, Canada, 1-800-563-3769, Vendor: Rudolph Bros. & Co., (614) 833-0707, Ext. 301, Contact: Keith, Part #, CLR 1556 / CLH 6510

XVIII. Appendix – Wiring Diagram



DATE	TITLE	
12/1/2008	MMI-IPC Inverter Project - Electrical Schematic	
PAGE	DRAWN BY	FILENAME
1 OF 5	FEWHITE	MMI-IPC SENSORS & PROBES & SCHEMATIC.VSD

XIX. Appendix – H-Bridge Current Sensor