

SOLAR POWER BOARD HARDWARE GUIDE

MetaFridge Solar Power Board Hardware Descriptions

Abstract

Detailed description of the solar power board in the MetaFridge.

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Introduction

The solar power board is a critical part of the refrigerator electronics in the MetaFridge; it controls many aspects of refrigerator performance. This document was written to provide a technical definition of each of its sections and the reasoning behind design decisions. The end goal is to provide enough information that the system may be tested for conformance, or used to accurately design the connected systems.

This document corresponds to Revision 4.1 of the solar power board, and it should be read in conjunction with the schematics. Those schematics are in two forms: a simplified schematic that shows the power flow, and full schematics of all the components on the board.

Below is a list of the hardware sections described in this document:

1. Overview of Features
2. Photovoltaic Input, Monitoring, and Availability Determination
3. AC Power Flow and Protection
4. AC Power Measurement
5. Primary DC Loads: compressor and refrigerator electronics
6. Power Harvesting and Prioritization
7. Microcontroller and Communications
8. Layout Considerations

Related documents:

- MF2SolarBoard R4.1 Schematics.PDF: Detailed schematics for the board
- solar_power_simplified.pdf: Block diagram that shows power flow
- WHO_PQS_E007_EHC1.1-Nov_1_2016.pdf: WHO PQS performance specification for solar direct drive surplus energy harvest controls
- WHO_PQS_E007_EHC01-VP.1-Nov_1_2016.PDF: WHO PQS verification protocol for solar direct drive surplus energy harvest controls

Overview of Solar Power Board

This section is best read referring to the simplified schematic.

Features

- Input from photovoltaic (PV) and AC power sources, selectable under microcontroller control.
- Monitoring voltage, current, and power of both inputs.
- Monitoring of load currents.
- Measurement of photovoltaic power availability as it changes with solar conditions.
- Control of refrigerator compressor to optimize cooling and match PV power availability.
- Power supplies for refrigerator electronics.
- Power harvesting (diverting power not needed by the compressor to other loads)

Power Inputs

The Revision 4 solar power board is more than a solar power board: it enables operation from both PV and AC power sources, and can be connected to both sources simultaneously.

The photovoltaic input can connect to a wide range of solar panels. It can accept input power from panels with open-circuit voltages up to 45V, though most typically 22Voc panels will be used. It is designed for currents up to 18A, to accommodate 22V panels with total ratings up to 300W. Not shown on the simplified schematic (but on the full

schematic page 2) are several other features. Reverse voltage protection allows panels to be connected with reverse polarity and not damage the system. Surge protection guards against transient overvoltages from nearby lightning strikes. Finally, an electromagnetic interference (EMI) filter reduces interference the power board can have on other equipment nearby.

The AC mains input can accept input voltages beyond the range normally thought of as “universal”. It works over the range 80V to 290V. The protection circuits shown in the simplified schematic (and in detail on page 4 of the full schematic) also contain EMI filtering and surge suppression. In addition, they have a protection relay that disconnects the system from the mains if the voltage goes outside the bounds of 80V to 290V. The protected AC is sent to an off-board 24V AC/DC converter; 24V is returned on connector JP8.

The power source, PV or AC, for the major loads is selected under microprocessor control using transistors Q20A/Q20B or Q26/Q27 acting as switches, powering the DC bus (node DCBUS on the schematics). This allows different algorithms to be used to choose whether the refrigerator is primarily powered by PV or AC, when both are available.

In general, it will not be possible to power the major loads by a combination of PV and AC, due to the voltage-current characteristics of PV panels and the AC/DC power supply. The panels most commonly used with the Solar MetaFridge have an open-circuit voltage about 22V; above that voltage, they will not produce any power. However, the AC/DC power supply creates 24V, which will keep the PV panels at 24V if both AC and PV switches are turned on. Likewise, if the system instead had PV panels with open-circuit voltage around 44V, their voltage would dominate the AC/DC supply (and indeed might damage it).

Measurement and Control

Most aspects of power consumption are monitored, both to understand system operation and to better control it. The input power (voltage, current, and power derived from them) is measured for both PV and AC inputs. The AC input also monitors the input frequency. The DC bus voltage is known, either the same as the PV array voltage, or 24V, depending on the power source selected. The current drawn by each of the major outputs described in the next section is measured.

Solar panels have a distinct voltage-current characteristic similar to that in Figure 1 (red curve). The short-circuit current, I_{sc} (the value when $V=0$), increases as the intensity of the illumination increases. Because power is the product of voltage and current, the maximum power point (peak of green curve) is somewhat below the open-circuit voltage, and changes with solar conditions.

The solar power board measures how much power is available by applying a load to the array, measuring the voltage and current, and computing power. It steps up the load, tracing the green power curve and searching for the maximum. The load may consist of resistors in a resistor bank, the compressor operating power, or a combination of the two. This estimate of power availability is continually updated to keep up with changing conditions.

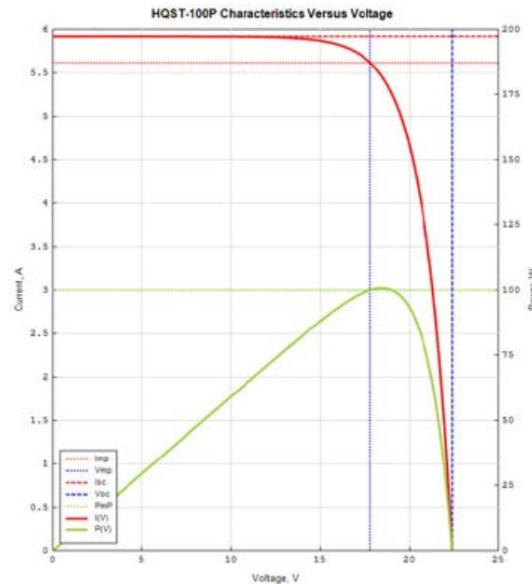


Figure 1: Example solar panel voltage-current and power curves at standard test conditions.

With power availability in hand, the microcontroller can select which loads to turn on. It will know if there is enough power to start the compressor, and if there is more power available than the compressor can use. Each of the power outputs described below can be enabled or disabled, and some can be controlled with finer resolution than that. Priority will be given to the compressor and refrigerator electronics, but extra power can be used for other loads.

Power Outputs

The compressor is the *raison d'être* of the solar power board: without it there is no refrigerator. The DC compressor used in the Solar MetaFridge is variable speed, which allows the solar board microcontroller to adjust the cooling heat transfer to maximize power available from the PV array. In addition to commanding zero speed, which lowers power consumption to a low level, it is possible to disconnect power to the compressor entirely.

It should be noted that the refrigerator electronics (center of the simplified schematic) are powered by the greater of the two voltages: PV, or 24V derived from AC. This architecture allows the power supply to be available regardless of the state of the power board microcontroller. Power to the compressor fan and the main board can be controlled by the microcontroller. This allows the system to turn off main board battery charging (which would typically be a morning activity) in order to start the compressor when the power available from the PV array first crosses the minimum threshold to start the compressor.

“Power harvesting” or “energy harvesting” are terms used in the solar refrigerator industry to refer to diverting unused available solar power from the refrigerator compressor to other loads. Usually, this diversion happens when the compressor is not operating. However, it is possible to have excess power available from the PV array even when the compressor is operating at full speed. Systems with more complex controls, like the Solar MetaFridge, are able to power more than one load at a time. The solar power board has three auxiliary power outputs in addition to the required compressor and refrigerator electronics; these outputs will be described in the next few paragraphs.

Two of these auxiliary outputs provide individually enabled, fixed voltages to power external loads. The 5V output is designed to act as a USB charger for up to 3 USB devices at 1.5A apiece. The 12V output can power devices that use an automotive power port (formerly cigarette lighter) connector.

The third auxiliary output is adjustable, and is sometimes referred to as the “High Voltage” Auxiliary output. High voltage is a relative term; in this case it means that the output is more than 12V, and can be up to the PV array operating voltage. This output consists of a DC/DC converter with output voltage and current limits adjustable by the

microcontroller. In addition to its input current, the microcontroller can monitor its output voltage and current and use those values as part of its control algorithm. Furthermore, there is a two-way serial data connection between the microcontroller and a load that is capable of communicating over the connection.

Thus, the High Voltage Auxiliary output can be used to power a variety of loads. Some of those are:

A battery

Output voltage and current monitoring enables the HV Auxiliary output to charge a battery pack at any voltage up to the PV array voltage. The battery could be used to store energy at the refrigerator for other types of loads, or could be external, with the ability to be used elsewhere once charged. Although the initial implementation of this circuit has been designed for one-way power flow to the battery, it is possible with a small change to enable two-way power flow. The battery would then be able to power the compressor for brief periods, such as to maintain it running when a cloud passes over the PV array.

A smart load or a smart battery

If the load has intelligence and can communicate over the serial data connection, then it is possible for the power board microcontroller to give a digital command consisting of the maximum amount of current or power the load should draw from the output. Likewise, the load can identify itself and request certain parameters, such as a particular voltage or current limit.

A commercial off-the-shelf (COTS) solar charge controller

These charge controllers are meant to connect between a solar array and a set of batteries. They expect that their power inputs will have the variable power characteristics of a PV array, and most modern units will strive to maximize the energy sent to the batteries by operating the array at its maximum power point. It is possible to use the controllable voltage and current of the HV Auxiliary supply to emulate a photovoltaic panel's output, tricking the COTS charge controller into drawing the desired amount of power while still operating the compressor.

As an example of how this would work, imagine that there are presently 200W available from the PV array. The compressor is running, but only requires 90W. Therefore, we could allow the load attached to the HV Aux output to draw up to 110W. In practice, we might limit it to 96W to give the compressor a bit of margin for changing solar conditions. If we set the output voltage to 16V and the current limit to 6A, the charge controller would draw up to 6A, and if it tried to draw more, it would notice that the auxiliary output voltage would drop. In order to maximize its power, it would reduce its current back to the 6A amount.

The details of emulating a PV array are a little more complex than the example, since a PV voltage-current curve is not a perfect rectangle.

Freezer

Since the maximum power drawn can be dynamically adjusted, a multitude of other load types can be contemplated. We have prototyped an ice-pack freezer that is powered by this output. Its microcontroller coordinates power drawn with the solar power board's microcontroller, allowing both compressors to operate at once.

Photovoltaic Input, Monitoring, and Availability Determination

Protection

The photovoltaic protection circuitry is on schematic page 2, "DC Power". Metal-Oxide Varistors (MOVs) and Gas Discharge Tubes (GDTs) in series protect against surges from lightning or other transient effects. The GDTs are chosen so that they will not conduct for PV voltages up to at least 50V, once they do conduct in a surge, they have a low on-state voltage. The MOV in series will absorb much of the surge energy and provide enough forward voltage that the

GDT will not continue to conduct from normal PV voltage after the surge completes. Transient voltage suppression diode D8 after the EMI filter helps clamp any remaining surge that has passed the filter.

In rare cases, the polarity of the solar array input will be installed in reverse. Without some protection, circuits can be destroyed or at a minimum the fuse will blow. Transistor Q28 acts as a low-loss diode. It will be off if the polarity is reversed, protecting the PCB. When the polarity is correct, it will turn on, minimizing the conduction losses in the diode.

The fuse is an automotive type DC fuse, rated at 20A to handle the peak current from a 300W PV array at about 17V maximum power point voltage.

Monitoring

The power board measures PV input power as part of the data acquisition functionality of MetaFridge and to control the compressor. Except for the current-sensing resistor R25, which is on the DC Power schematic sheet, the monitoring circuits are on sheet 3, "DC Monitoring." The Analog Devices ADE7903 analog-to-digital converter (ADC) is designed for energy metering applications, and contains two ADCs so that it can measure voltage and current simultaneously. It is compatible with the ADE7912 isolating ADC used for AC power measurement, using the same serial peripheral (SPI) bus to communicate to the microcontroller.

The sensing resistors were chosen so that the maximum input voltage for accurate digital conversion is 64V. Likewise, the maximum current that can be accurately measured is 31.25A.

The ADE7903 has a DC offset in its output codes that varies from part to part and to some extent with temperature. Transistor Q11 is used to short the voltage divider to measure and null the offset. The current offset can be measured at nighttime when there is no PV input, or by turning off Q26 and Q27 to remove almost all load to the PV panel.

Photovoltaic Power Availability

The circuit that measures PV power ability is on the lower half of sheet 3. It consists of a binary-weighted (or nearly so) array of 6 resistances: 2, 4, 8, 16, 33, and 66 ohms. These resistances can be placed across the PV array, either alone or in combination, to load it down briefly. During that time, the microcontroller will measure PV voltage and current. The applied load is changed and a new set of measurements taken in order to build up a peak power curve like the green trace in Figure 1. Once the peak has been found, that is the instantaneous power availability.

The resistors used on the PCB are only rated for 35W continuous operation (25W for R2, R27, & R28) when operating at room temperature. The power board compartment is unlikely to be 25°C all the time, and the resistors themselves will be warmer still. Furthermore, if the PV voltage is 45V, the power consumption in the 8 ohm resistors will be about 250W. Therefore, it is important to operate these resistors at a low duty cycle so that the average power will be low enough not to overheat them.

If the compressor is operating, it is also possible to adjust the compressor speed and measure the change in panel voltage and current. This is a way to gauge the power availability without using load resistors and their concomitant heating. In practice, a combination of techniques is used because the compressor may be running at full speed, or the available power may exceed that drawn by the compressor.

Integrated circuit U6 is placed within the resistor bank so that it can measure the localized temperature and reduce the power availability duty cycle if the area is overheating.

AC Power Flow and Protection

Power Flow

AC power flow is documented on sheet 4 (“AC Power Input”) of the schematics. Grid or generator power is connected to JP4 on the upper left side. Power flows through protection and EMI filtering circuitry. JP3 provides a connection to send AC power to the off-board DC power supply.

Protection Elements

The protection elements fall into three general categories: overcurrent, sustained over voltage or under voltage, and surge overvoltage. The 3A slow blow fuse is sized to handle steady-state compressor run current, but not continuous start current. A fuse with 500VAC rating was chosen because sometimes mains power outside the normal range is experienced.

The voltage protection relay, K1, was selected for the purpose of disconnecting the rest of the system from the mains should the mains voltage fall outside the range 80V-290V. Field data collection before the MetaFridge design process began identified health facilities that experienced voltages between 300V and 450V. One data point was 700 V, though it was not confirmed whether that was a brief surge, noise, or a sustained condition. The dielectric between open contacts in the relay is rated at 1250VAC, well above expected input voltages.

The board has differential mode surge suppression components in two places: before the voltage protection relay and after it. When the voltage protection relay is conducting, the lower clamp voltage of the second metal-oxide varistor (MOV) should protect the electronics. When the voltage protection relay is not conducting, the higher clamp voltage of the front-end MOV and gas-discharge tube (GDT) combination protect the relay and also allow for sustained input voltages up to 700VAC without damaging the equipment. Likewise, the common-mode MOVs and GDTs protect the EMI filter capacitors and other insulation in the system. The MOVs were chosen to handle up to 6kV surges.

Note that connectors JP3 and JP4 are capable of 13 A continuous, and therefore can handle well in excess of the continuous current that could flow with a 3 A fuse.

Protection Control

The voltage protection relay is controlled by the comparator circuits on sheet 5, “AC Protection Control.” These circuits turn relay K1 on when the input voltage is within the desired range.

The power supply for protection relay control is a capacitive-coupled supply using C31; it is not safety isolated from the line voltage. C31 has a very high voltage rating so that the input voltage can be up to 700V without damaging the system. The amount of available current is dependent on input voltage, so in ordinary circumstances, that current is low. K1 is a bistable (set-reset) type relay so that it does not draw continuous power, and capacitors C32 and C33 supply energy to change its state. Overvoltage LED D18 serves two purposes: it notifies a technician that the input voltage has exceeded 290 V, and it also adds load to the power supply during high voltage conditions. This added load diverts power from the clamp circuit of R105, D16, and D40, keeping those parts of the circuit at a cooler operating temperature in overvoltage conditions than they would without the LED.

AC Power Measurement

The power board measures AC power as part of the data acquisition functionality of MetaFridge and to decide if the compressor should be operated from AC. It measures input voltage and current even when the protection relay is not conducting.

The Analog Devices ADE7912 isolated analog-to-digital converter (ADC) ICs is designed for energy metering applications, and contains an isolated power converter, isolating data connections, and multiple ADCs on the AC side of the isolation

barrier. Note that the ADE7913 is a pin- and code-compatible substitute in this application; some board builds have used the substitute IC when the original is not in stock.

Both mains and PV measurement ICs are connected to the microcontroller via a serial peripheral interface (SPI) bus. They require an 8 MHz clock, which is supplied from one of the microcontroller's timer-counter peripherals. This allows the application to stop the clock and greatly reduce the power consumption of the ADCs when they are not needed. "Data Ready" outputs of the ICs are used to interrupt the microcontroller when data is ready, which is at a rate of approximately 1 kHz (actually due to achievable clock frequencies, more like 977 Hz).

The current sensing resistors are sized so that the ADCs will not saturate for currents up to 31.25 A peak, or assuming a perfect sine wave, about 22 Arms. Similarly, the voltage dividers were chosen for 1000 V peak, or about 707 Vrms. R99 is a high-voltage resistor that forms the top portion the voltage divider. Ferrites are used to attenuate high-frequency noise before it can radiate from the board or AC power lines.

Primary DC Loads

Compressor

Back to schematic sheet 2, DC Power. Power is switched from the DC bus to the compressor with Q4. PV power to the compressor flows through JP6 pins 5 and 7. The signal from the microcontroller that turns on Q4 (PWR_SEL.COMP_PWRD) also turns on Q23 and Q24, applying 5 V to the communication circuit of Q5, Q6, and Q12. This circuit translates between the microcontroller's UART transmit and receive pins and the single-wire communication bus used by the compressor controller, connected to JP6 pin 4 (the "D" signal).

The compressor controller has an enable signal, or "T" for thermostat, which internally has a pull up resistor to 5 V. To enable, the "thermostat" switches the signal to ground (the "C" or common connection on JP6 pin 6). Q9 takes the place of that thermostat, but the signal follows a circuitous route. Q9 pulls down on JP6 pin 1. The fridge has a mechanical safety thermostat connected between pins 1, and 3. The PCB connection between pins 2 and 3 connects that thermostat to the "T" connection of the compressor controller. Thus, the mechanical thermostat is in series with the enable pull-down of Q9. Ordinarily, the thermostat is a closed circuit; it only opens as a safety device when the system becomes too cold, preventing subfreezing of the ice block and the risk of freezing vaccines.

Refrigerator Electronics

As mentioned above, DC power for the board, and indeed all the refrigerator monitoring electronics, is supplied either by an off-board AC/DC 24 V power supply or from PV. The AC/DC supply, a Mean Well HLG-150H-24, is designed for LED lighting applications, and has a wide input voltage range of 90VAC to 305VAC, roughly matching the desired input range for compressor operation. Empirical testing shows that they operate down to at least 80V. Sheet 6, "LV Power," shows the diode-OR connection of D43 and D44, selecting either PV voltage or AC-derived 24 V as the source for monitoring electronics supplies. The DC/DC converter U5 drops this voltage to 12 V, which is used to power the other circuits in the fridge. Other, lower-voltage (5 V and 3.3 V) supplies are derived from this one.

Both 12V and 5V are sent to the main board via JP9 (sheet 10, "Microcontroller"). 12 V is used to charge the main board's Li-ion battery and 5 V to supply the control microcontroller, the Linux telemetry module, and 3rd-party telemetry boards. The main board sends back its battery voltage on the power node named "VBAT_UNREG" (also on JP9), and can turn that voltage off to save power. As shown on the LV Power sheet, the battery voltage can also be used as the source for the 3.3V supply. This allows power monitoring and data processing circuits to operate even in a power outage.

The fan that cools the compressor compartment is supplied with 12 V from connector JP7. The control processor turns it on and off as needed with signal FAN_ON.

Power/Energy Harvesting and Prioritization

As noted above, the solar power board has three outputs that allow the system to “harvest” excess energy from the PV array that is not used for cooling the refrigerator. These are called “auxiliary” loads in the schematic.

Low Voltage Auxiliary Loads

The so-called “low voltage” outputs are on schematic sheet 7. U10 and U12 are DC/DC converter ICs, tuned to 13.8 V and 5 V, respectively. The 13.8 V output is used for a “12 V” automotive “cigarette lighter” output on the side of the fridge, while the 5 V output is connected to two USB-A receptacles. These can be used for battery and USB charging applications. The DC/DC converter ICs are rated for a maximum 5 A, though we have found that about 2.0 – 2.5 A output current is the comfortable thermal limit.

Integrated circuit U14 is a quad-input analog-to-digital converter, it is used in a differential configuration to measure the voltage across current sensing resistors R118 and R127 on the left side of the sheet. These measure the input current to the DC/DC converters to gauge the power drawn from the DC bus.

High Voltage Auxiliary Load

The third output is meant for higher power loads. Called the “High Voltage Auxiliary”, it is on schematic sheets 8 and 9. It consists of a DC/DC controller and gate driver IC U23, power MOSFETs Q30 and Q32 in a half-bridge configuration, and associated inductors and capacitors. This controller can work in either constant-voltage or constant-current modes from 0 V to the PV array voltage, and from 0 A to 8 A.

The output voltage and current set points are chosen by the microcontroller and output as pulse-width modulation signals on the nodes labeled HVAUX.VSET and HVAUX.ISET. Because there is a current-sense resistor R160 (upper left) between the microcontroller ground and the DC/DC converter ground, these PWM signals are buffered by the NMOS and PMOS transistors Q35, Q36, and Q38 to remove the effect of voltage differences as the current changes. Then the PWM is filtered and buffered by U24. The voltage set point is fed into the output voltage feedback loop through R182.

The current limiting feedback loop is a little more complicated. The LM5117 has a current monitor output, which is an averaged value of the sensed inductor (L3) current. This node is labeled HVX_CM on the schematic. It is added to the setpoint through the resistive network of R191, R192, and R195. Or more precisely, the two are subtracted because the setpoint’s value *decreases* for greater desired current. Precision shunt regulator U25 and transistor Q37 create a current source based upon that difference. The current is added to the RAMP input of U23, the main part of which is derived from R170 and C160, per the datasheet application information. The effect is to increase the ramp slope when current is higher, thus shortening the on-time of Q30 and lowering the output current.

During early testing, it was found that the feedback node experienced integrator windup during constant-current operation. This led to U23 operating in a hiccup mode where it would output for a while, then shut down, then operate again. Clamping the feedback compensation node HVX_COMP to a maximum 2.1 V prevents windup beyond that point, and eliminates the hiccup. Zener diodes, especially ones with such low Zener voltages, are not precise enough to reliably fix the issue. Thus U29, a 400 mV voltage reference and buffer amplifier, is used to create a 2.1 V clamp. Schottky diode D54 ensures that the clamp only sinks current so that the clamp cannot drive the compensation node higher during normal operation.

Other parts of the HV Auxiliary output are on schematic sheet 9. U13 and U26 are ADS1115 ADCs that measure various parameters of the DC/DC converter. U13 measures compressor current and the *input* current to the HV Auxiliary output’s DC/DC converter, much as U14 does for the low voltage outputs. This provides a total power level drawn from the DC bus. U27A and U27B are presently unused and not connected. They are an option to add an offset to the current measurement, in case the auxiliary output is configured for bidirectional current flow. In that case, the offset would ensure that the inputs to U13 do not go negative. U26 measures the HV Auxiliary output voltage, and U23’s current monitor output, to track operation.

The board has the ability to communicate with a load containing a microcontroller over a wiring harness connected to JP14. One of the microcontroller's UARTs is used for serial communication to coordinate power draw between the fridge and the extra load. Power to the load will be turned off when the fridge's compressor is operating, unless there is sufficient excess power available for the load. In order to continue communication with the load's microcontroller, linear regulator U28 provides 3.3 V at up to 200 mA, and can do so when the primary power is disabled. This power output can also be disabled to conserve battery at night, by lowering the HVAUX.FC1 signal.

Prioritization

Each load can be individually enabled in a priority order. The present default order is:

- smallest power level (5 V) first
- medium power level (12 / 13.8 V), if extra power is available
- highest power level (HV Auxiliary), finally, if even more power is available

Microcontroller and Communication

The microcontroller on schematic sheet 10 serves as the central communication hub for the board. It gathers voltage and current data for the inputs and outputs and computes power and frequency from them. It controls power flow to the outputs.

Data acquisition

The data collected and computed are sent to the DAQ portion of the main board over a serial connection; the signals are named UART_PWR2DAQ (for communication from the DAQ to the power board) and UART_DAQ2PWR. Microcontroller code also uses the input voltage and frequency values to determine if solar or mains power is acceptable for a compressor run. If so, it raises the DC_OK signal to the control processor. Signal PWR_WAKE is used to signal to the DAQ that power data will be sent soon, to wake up the DAQ processor if it is sleeping.

Firmware updates

The process of updating firmware that the DAQ processor has received over the air is as follows:

- When the DAQ recognizes it has a firmware update for the power board, it sends a message on the serial connection between the two. This message replaces the normal message that means "yes, I am ready to receive power data".
- The DAQ also raises the PWR_WAKE hardware signal.
- Upon receiving this message, the power microcontroller reboots itself.
- The bootloader checks PWR_WAKE, and if it is high, starts the process of receiving the firmware update and storing it in its flash memory.
- Once complete, the DAQ drops the PWR_WAKE signal, and the power microcontroller reboots again.
- This time, the bootloader senses that PWR_WAKE is low, and jumps to normal code execution in the new firmware.

Debug console

Connector JP12 is known as the debug port. Diagnostic information is sent to one of the microcontroller's UART modules, connected to this port, and it can be read by a computer. The pin configuration was chosen so that a standard USB-UART cable from Future Technology Devices International (FTDI) will connect directly to it. This cable is FTDI part number: TTL-232R-3V3. The black, ground wire of the FTDI cable is oriented on the left side of the header, near the silkscreen label "BLK". This orientation is also used for the various processors on the main board.

The firmware also listens to the debug UART for a small set of commands. These change the output logging level verbosity and also read/write a buffer of the log output from/to internal non-volatile memory.

Other

A signal from the control section of the main board (CTL_PCOMP) indicates that cooling is needed. This pin is read by the firmware to initiate compressor operation.

In early versions of the circuit board, we found that the real-time clock (RTC) in the SAMD20 was not convenient to use. It does not have a separate power domain, so power to the rest of the processor cannot be removed to achieve a low power mode. That led us to use the Maxim DS3231 (U3) as an external RTC. Absolute time is not needed for the operation of the power board; only relative time. However, absolute time does help the technician when reading the information printed to the debug port, described next.

Jumpers JY1 and JY2 are left over for compatibility with an older version of the design. They either connect two signals to pins of JP9, or leave those pins unconnected. This feature was intended to provide the ability to reset the microcontroller from the main board and reprogram it over a serial line. So far, this functionality has not been implemented.

However, signal PA00/TEST_MODE is used to enter self-test mode. When using the power board tester, connect PWR_SEL on JP9 to PA00 by placing the jumper on pins 2 and 3 of JP2. Be certain to replace the jumper onto pins 1 and 2 after the self-test process to minimize the risk of inadvertently entering self-test mode.

Connector JY6 is a header with extra signals or signals that might be used for alternate purposes. It also has connections to the power supplies. It is also not inserted; however some of the pins are used by the PCB tester.

Layout Considerations

Separations

We used separations as specified in IEC 60950, using pollution degree 3 and material group IIIb. We used the respective voltages and insulation types appropriate to the different parts of the circuit. Because the PCB has a conformal coat, the “uncoated creepage” column was ignored. Also, clearance is greater than coated creepage, so we used the clearance column The calculator at www.creepage.com was used to derive some of these values.

Signal Type	Required insulation type and working voltages	clearance, mm [mils]	uncoated creepage, mm [mils]	coated creepage, mm [mils]
PV positive to PV negative	Functional or Basic insulation: 60 Vdc	0.8 [32]		
PV positive or PV negative to Earth	Basic: 60 Vdc	0.8 [32]		
PV positive or PV negative to safety extra low voltage (SELV)	Reinforced: 60 Vdc	2.4 [102]		

Line to Neutral before protection relay	Functional insulation, 707Vrms → 1000Vpk	4.2 [166]	11.3 [447]	2.4 [95]
Line to Neutral after protection relay	Functional insulation, 300Vrms → 424Vpk	3.0 [118]	5.0 [197]	0.8 [32]
Line or Neutral to Earth Ground before protection relay	Basic insulation, 707Vrms → 1000Vpk	4.2 [166]	11.3 [447]	2.4 [95]
Line or Neutral to Earth Ground after protection relay, or to isolated AC	Basic insulation, 300Vrms → 424Vpk	3.2 [126]	5.0 [197]	0.8 [32]
Line or Neutral to Secondary circuits (those supplied by 12V, 5V)	Reinforced insulation, as this might be an <i>unearthed</i> secondary separated extra-low voltage (SELV) circuit. 300Vrms → 424Vpk	6.4 [252]	10.0 [394]	1.6 [63]

Trace Widths

The input fuse for the power board is rated 2 A, so traces that carry AC power to the AC/DC converter should be able to withstand at least that much. The DC fuse is rated 20 A, to accommodate full power from the PV array running the compressor and a large energy harvesting load.

Trace sizes were chosen using the calculator from <http://www.smps.us/pcb-calculator.html>, based on IPC-2152. Parameters are: 40C rise, 1 oz. copper, 0.062" PCB thickness, and no nearby copper plane to dissipate heat. In general, traces are made wider than this minimum (or made in multiple layers in parallel), except in a few tight areas of the PCB for short distances.

Current	Width, thousandths of an inch (mils)
1A	4
2A	14
3A	27
5A	62
10A	200
12A	272

15A	395
20A	641
25A	933

Electromagnetic Compatibility (EMC)

There are a number of circuits on the PCB that are sources of conducted and radiated emissions. Most notable are the ADE7912 power measuring ICs, as they have high frequency clocks to transmit power and data across the isolation barrier. Others include the microcontroller and various power supplies. A number of measures were included in the design to minimize emissions and also the effect of external radiation on the board. External to the PCB design, the board is mounted in a metal enclosure.

Analog Devices recommends creating a stitching capacitor across the isolation barrier of the ADE7912 by using different PCB layers as plates of the capacitor (see Analog Devices Application Note AN-1332). However, the advice we received from a safety lab (TUV SUD America) was to use creepage values for both in-plane interior separations and between-plane separations. For the high voltages we designed for, they recommended 0.56mm separations. With that kind of separation and the limited space available on the PCB, it is difficult to make more than a tiny capacitance. Instead, C84 and C85 are used as the stitching capacitors.

Other EMC measures include ferrites/capacitor filters at connectors, and a 4-layer PCB to provide a good ground plane for the microcontroller, power supplies, and other high-frequency sources.

- End of document.