An Approach to Lithium-Ion Battery System Design

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What's the appeal?

- Higher power and energy density
  - In terms of both weight and volume
- Near-constant voltage over usable range for LFP
- Very little drop in cell voltage under heavy load
- No significant Peukert effects
- High charge and discharge rates
- No hazardous gases to vent
- Possibly lower life-cycle costs than lead acid

Objectives
(for my own system)

- Relocate batteries, inverter, charger from storage bay near generator to dead space at rear
  - Want to reduce total space occupied by system while increasing capacity
- Want to be able to charge at rate close to generator's capacity to minimize fuel consumption
  - Influences cell type and configuration to some degree, though any Li system will be an improvement over FLA or AGM.
  - Full charge with lead acid batteries requires long period of time at low charge rate (~few hundred watts) while basically idling 12kW generator
- Significantly increase usable capacity
  - Starting with 6 T105s that are several years old. 3*(200Ah)*(12V)*(50% usable for reasonable life)*(they're old)=<3kWh
- No transfer switching
  - Even the short time it takes for a transfer switch to operate can affect some electronics.
  - Want to be able to feed power to batteries and run house at same time—even if shore power is limited.
- Need to be able to charge chassis batteries from house, ~~charge house batteries from alternator, and start generator from either source~~
- Enough power to run air conditioning for ~1 hour (at least).
- Keep it simple to operate and maintain
- No fires, explosions, leaks, or funny smells

Considering Higher (48V) DC Voltage

Pros:

- Smaller copper wire ($$), less lossy
- Greater selection, cheaper inverter options
  - Inverter prices generally scale with DC current ratings, not total power
- Packaging and battery management simplified
- RVIA low voltage standard no longer applies

Cons:

- Need to convert back to 12V for some loads
  - Easy for small loads, not so easy for high-amperage loads like leveling jacks
- More complicated management with 2 DC voltages
- Slightly higher risk of shock

Why 48V?

- Inverter selection. 48V is pretty common for home off-grid systems (along with telephone systems and others)
- High enough to be efficient and cost effective, without introducing HV safety concerns/costs.
- Pre-configured battery modules

Main Components

- Batteries
- Charger
- MPPT controller
- Solar panels
- 48V-to-12V buck converter
- ~~12V-to-48V boost converter~~
- Inverter

Batteries

- Before we talk about specific batteries, let's take care of some terminology.
- Forget about ratings in Amp-hours.
  - It's only relevant in comparing batteries of the same type and design.
  - Cell voltages are considerably different between FLA and lithium-ion batteries, and even quite different between different lithium chemistries.
  - When combining batteries in series-parallel configurations (e.g. 6V batteries in 12V system), you have to keep track of configuration when adding capacities.
  - Instead, we care about the amount of stored energy (measured in kWh), and the maximum charge and discharge rates (in kW)

How do I figure out what I have now?

- 6V x 225Ah = 1350 Wh = 1.35kWh
- However, as a general rule, for reasonable battery life, it's necessary to limit the depth of discharge to 50% for a lead acid battery.
  - This means that each T105 stores 0.675kWh of usable energy, drawn over 20 hours
  - Thanks to Peukert effect, faster consumption reduces this number further.
- 6 T105s would then be no more than 4.05 kWh of usable energy (when new), weighing 372 lbs. (10.9Wh/lb)

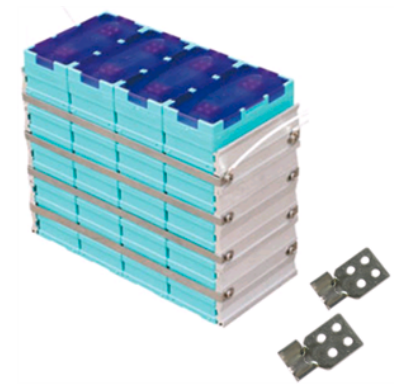
What about for lithium-ion batteries?

- Different chemistries operate at different cell voltages, but also have ratings in Amp-hours
- Calculate the capacity in kWh for a particular cell, and use 80% depth of discharge:
  - 100Ah CALB 3.2V LiFePO4 cell would store 0.256 kWh, and weigh 7.5lbs (34.1Wh/lb)
  - Roughly 16 cells (120lbs) would be equivalent to 6 T105 batteries

8.62 x 5.59 x 2.63 inches

Common Lithium Battery Form Factors

- Pre-assembled batteries
  - Ready to install, many incorporate battery management systems.
  - Usually made up of LiFePO4 prismatic cells
- Prismatic cells
  - Easiest form factor to work with.
  - Threaded holes for terminal connections, many designed around a system of bus bars to make series and parallel interconnections easy.
- Pouches
  - Usually best capacity/cost ratio, harder to package. Highest specific power.
  - Must understand thermal control when packing tightly together.



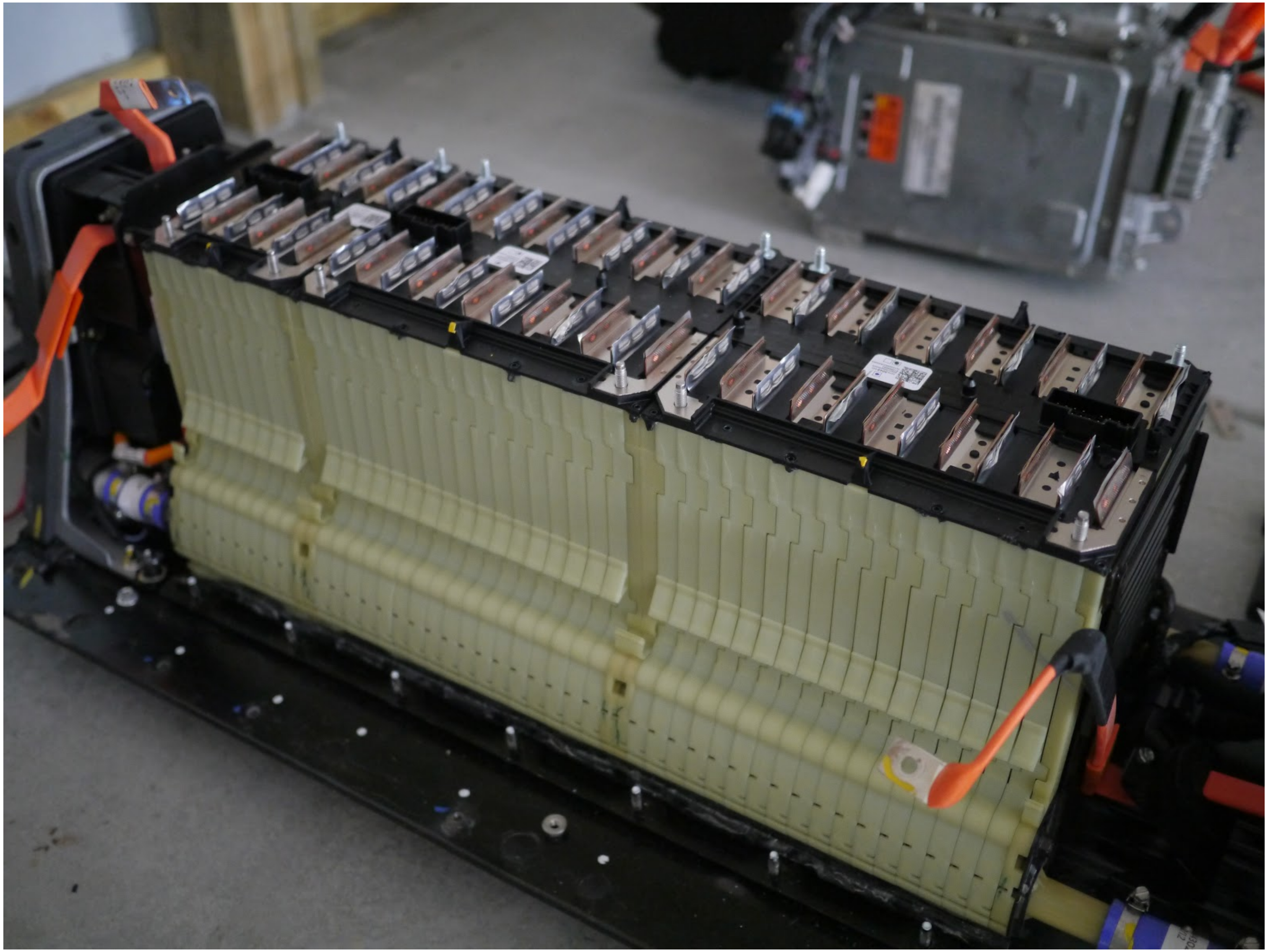
All three form factors shown here are lithium iron phosphate batteries (LiFePO4, or LFP)

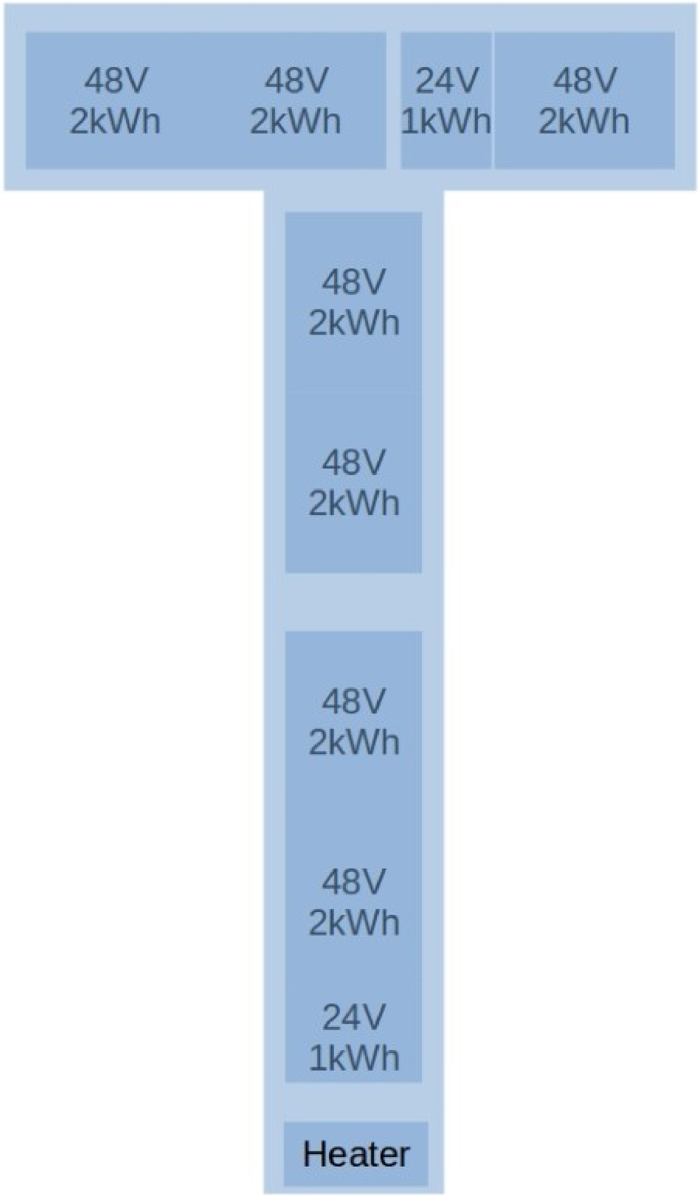
Common Chemistries

- Lithium iron phosphate ($LiFePO_4$, LFP)
  - Available in prismatic cells, easy configuration, probably most robust of any commercially available cells.
  - Easily sourced in cell sizes from 40-200Ah
  - Generally 3.2-3.5V/cell
- Other chemistries are not readily adaptable to RV use (cost, safety, availability concerns)

- Lithium manganese spinel
  - Essentially same chemistry as everyday consumer batteries (phones, laptops, etc.)
  - Most extensive application is Chevrolet Volt
    - 16kWh total capacity, 288 cells
    - 4.2V/cell at 100% charge
  - Including used packs, by far cheapest acquisition cost

Another Reason for 48V




48V
2kWh
48V
2kWh
24V
1kWh
48V
2kWh
48V
2kWh
48V
2kWh
48V
2kWh
48V
2kWh
24V
1kWh
Heater

Charging a Lithium-Ion Battery Bank

- Will an existing charger “work” on a 13.2V lithium-ion battery pack?
  - Maybe. On a 3-stage charger, bulk charging will be current limited by the charger, float stage may not be high enough, or too high, to reach full charge.
  - It's also possible to overcharge a lithium-ion bank. The voltage rise nearing 100% SOC can be very quick, and many 3-stage chargers do not switch to float mode fast enough.
  - More importantly, an existing 3-stage charger can be expected to charge much more slowly than what the battery bank can handle.
    - This means longer time running the generator!

Do I need a battery management system (BMS)?

- A battery management system connects to individual cells to monitor cell voltages. Many also control a shunt, so that individual cells can be taken out of the charging circuit when fully charged.
- If individual cells are properly connected and at the same state of charge when connected, detailed monitoring is not really needed any more than with lead acid systems.
- State of charge cannot be effectively estimated with voltage, so some sort of monitor keeping track of net power in/out of battery is necessary.
- Lithium-ion batteries can be severely damaged, if not rendered unusable, with as little as one discharge too far. A low-voltage disconnect is a must to protect the batteries.
- A battery management system does provide health information about individual cells that allows you to know more about what's going on, and can make re-balancing cells easier (but that shouldn't be needed).

How complicated is the charging process?

- Simpler than lead acid.
- Provided voltages are properly set, a single “bulk” charging stage is adequate.
  - Remember, generally we want to operate between 10% and 90% state-of-charge, which is mostly the flat-voltage region. The key requirement is the ability to set the charge voltage correctly.
- Depending on the capability of the charger and batteries, thermal management and current limits may be necessary.
  - Since these cells can be damaged by charging at elevated temperatures, a temperature cutoff for the charger is recommended. This also prevents overheating when charging at a high rate.

Are there good chargers already available?

- The best (but pricey) charger option is offered by eMotorWerks.
- Open-source hardware and software, available fully assembled or as a parts kit
- 12kW charge rate, 97% efficiency, power-factor corrected.
  - Even at this rate, a Volt battery pack is being charged at only a small fraction of what it can handle!
- Any input voltage or frequency from 85VAC (120VDC) to 400VAC
  - No more worries about low voltage at the pedestal!
- Software-selectable voltages, and programmable current limits
  - In other words, it can be set to charge at <15A on a 15A outlet, or 50A 220V when that's available.

Are there good chargers already available?

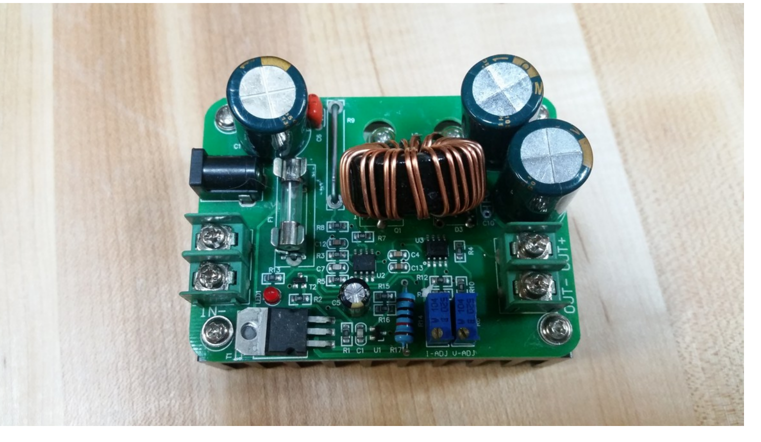
- Morningstar's MPPT controllers can accept power from a DC power supply, and have configurable charging stage voltages.
- Some 48V inverter-chargers already have charge profiles for some lithium-ion chemistries.

48V Inverters

- Lots to choose from
- Many offer split-phase 220V output
- Have to watch for 220V only inverters
  - Though a center-tap isolation transformer could make this workable
- Must be at least able to configure for 60Hz operation (remember, most of the rest of the world operates on 50Hz)
- Many have charge controllers built-in
  - Some even have dedicated wind/solar inputs with MPPT algorithms
- Surge capacities are typically very high—often 5x steady-state rating
- Cost per kW AC power out is generally lower than an equivalent 12V inverter

Charging from Truck Alternator

- Not all that much power can be expected
  - Typical 160A (peak) alternator outputs <2kW, and still has to run truck systems
- Need to step up to 48V battery voltage
- Need to limit current drawn from 12V system

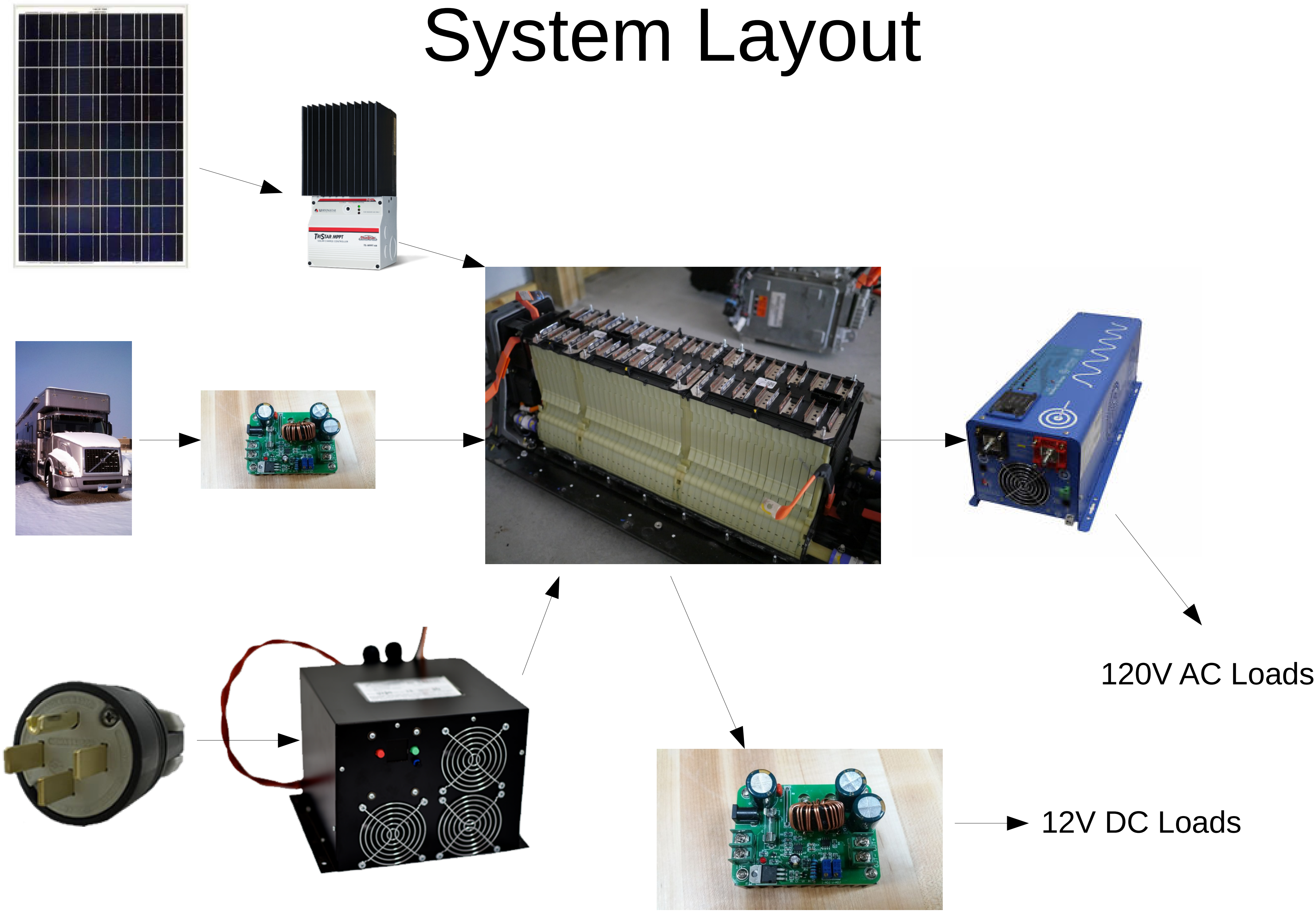


50A at 12V input, $30

Supplying 12V Loads

- What's left after AC loads?
  - Leveling jacks
  - Water pump
  - Lighting
  - 12V outlets
  - Radios
  - Antenna amplifiers
  - Refrigerator, water heater, and furnace controls
  - Air conditioning thermostats
- All except leveling jacks easily serviced by buck converter located at DC load center.
- Unlike when operating a normal battery system, buck converter will provide a much more stable DC voltage
  - Lights won't dim when the water pump is on!

System Layout



Now the fun stuff!

- That was all theory, and what I thought I knew at last year’s rally.
- Actually buying a battery pack and building the system is (of course) different
- To make sure I didn't end up with a bunch of expensive paperweights, the system is being built in stages.

Buying the Battery

- There are several databases of junk yards where you can find parts inventory.
- Cheapest battery pack in the country when I started looking was less than 15 miles away, so I went to take a look.
  - It was being stored on a pallet outside, and the yard wouldn't budge on a $400 core charge. Pass.
- Next one I would cross paths with was just outside Dallas. A little more expensive asking price, but $15 core charge (?!?!) was waived.

Texas Drivers Wreck a Lot of Cars!

Challenge

- Getting a 430 lb battery pack transported in a 4-door car
- Needs to be loaded quickly with a forklift—not exactly the only customer pulling up to the dock that day.
- Basically, we want to put an ET Junior in the trunk, but with a weird “T” shape

It fit, but even lithium-ion batteries aren't light

Now what?

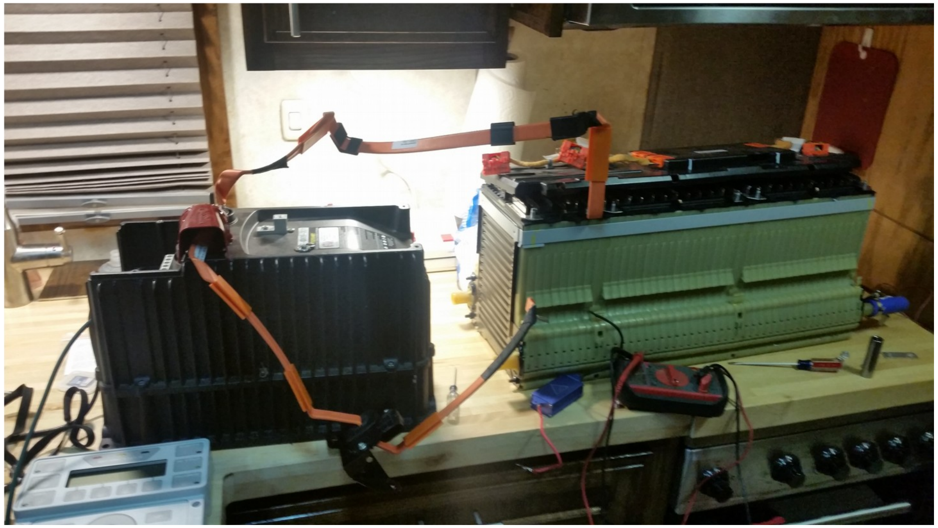
- Battery needs to be out of car to transport bike to race in 36 hours
- No extra hands
- No big tools
- Has antifreeze in cooling loop
- Can't make noise late in RV park

Disassembling in Place

- Composite cover held on by a bunch of bolts, lifts off easily in one piece. Lightweight part—10lbs max.
- First order of business is reducing the chances of shock. ~300V DC wouldn't be fun.
  - Main cables between each of the 3 main sections disconnected
  - Measurements showed all cells to be within 0.01V of each other
- Coolant hoses between section at top of “T” and the rest looked to be the high point in the system. Lines disconnected, module unbolted from base plate.
- Biggest section has to come out first. Weight approximately 175 lbs.
  - Don't tip, or car will smell like antifreeze forever.

Getting the big section into RV was not easy...

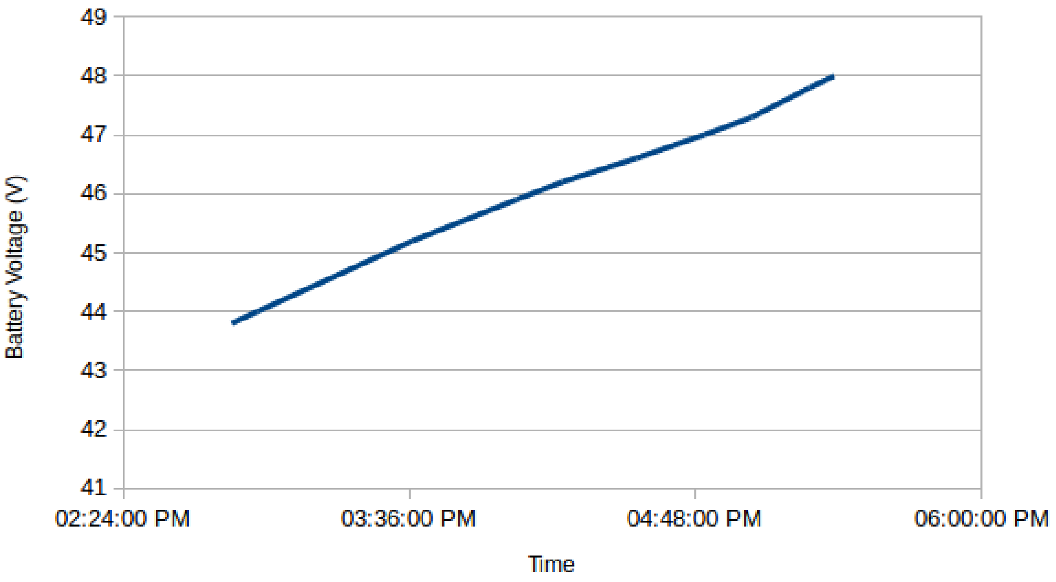
First attempt charging



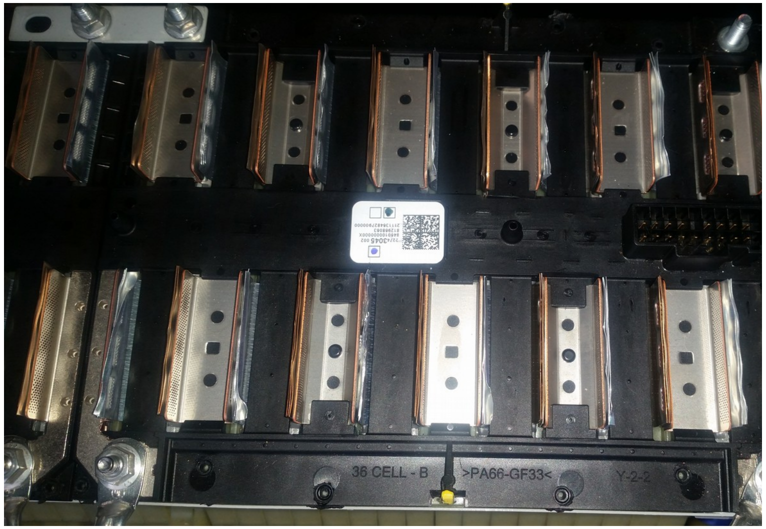
- Used 24V inverter/charger on one 24V section
- Found that lowest configurable voltage cutoff for bulk charging would be too high for battery bank
- Li-ion batteries can charge capacitors inside inverter very quickly!
- Still useful—got an idea of heating, learned a few things about making connections under plastic cover easily

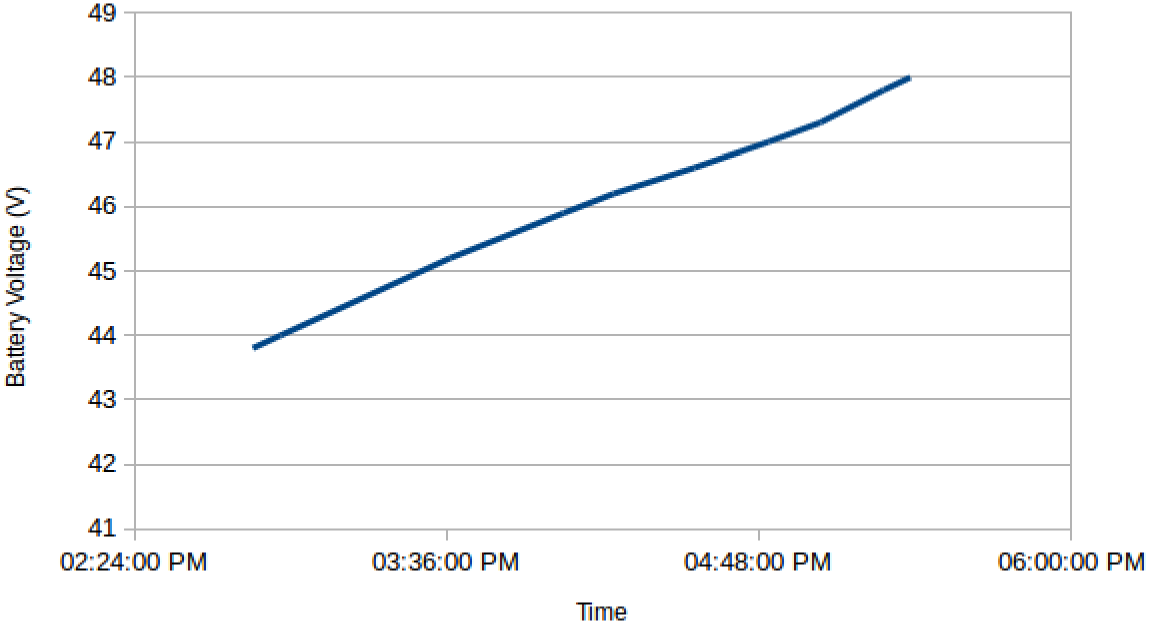
Second charging exercise

- Constant-current mode charging with 48V charger on inverter
- Manually stopped charging
- Recorded voltage vs. time (proportional to power in)
- Drop after stopping charging <0.5V



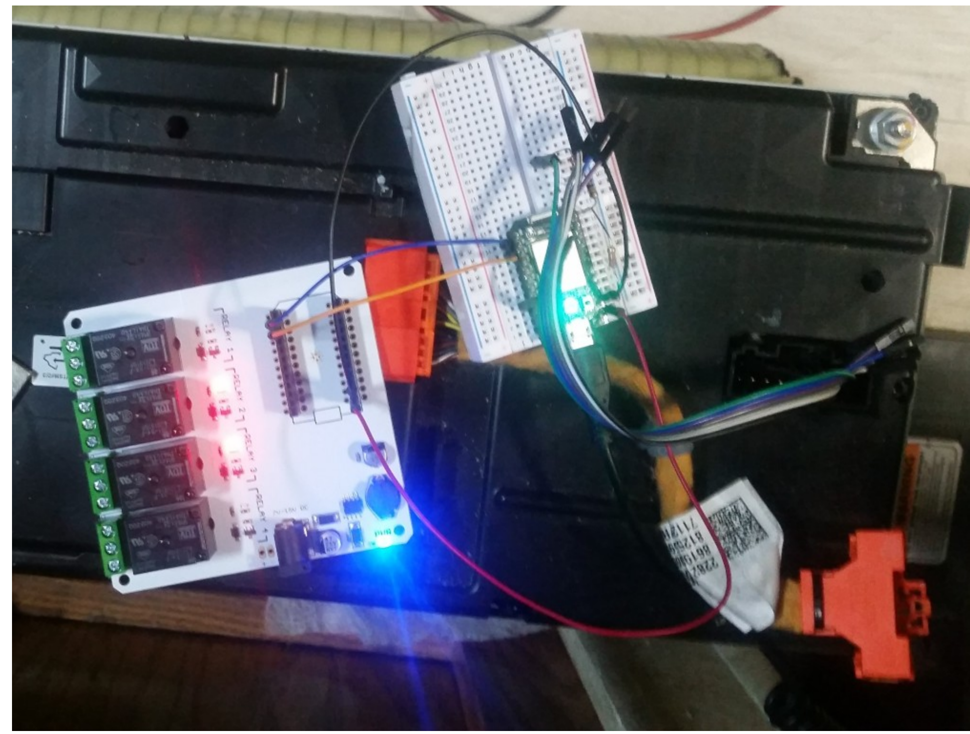
Second charging exercise





Charger Controller

- Couldn't find what I needed, so built my own
- Voltage tells us state of charge—no need for fancy monitoring to really know (as with LA or LFP).
- If cell voltages are the same, state of charge is the same
  - Cell balancing, if needed, is simple and boring
- Voltage divider circuit gets battery voltage down to voltage compatible with analog input on microcontroller
- Controller is same as Wednesday's workshop
- Measures module voltage, and battery pack's internal thermistors
- Separate relays for enabling charging and discharging



Skipping a bunch of bench testing...

- Built platform above floor, in dead space below bottom of cabinet
- All 3 battery sections would fit, except long section doesn't fit through cabinet doors.
  - Currently, it sits on the floor below the shelf.
- Forward section has left the RV for another project...

Safety

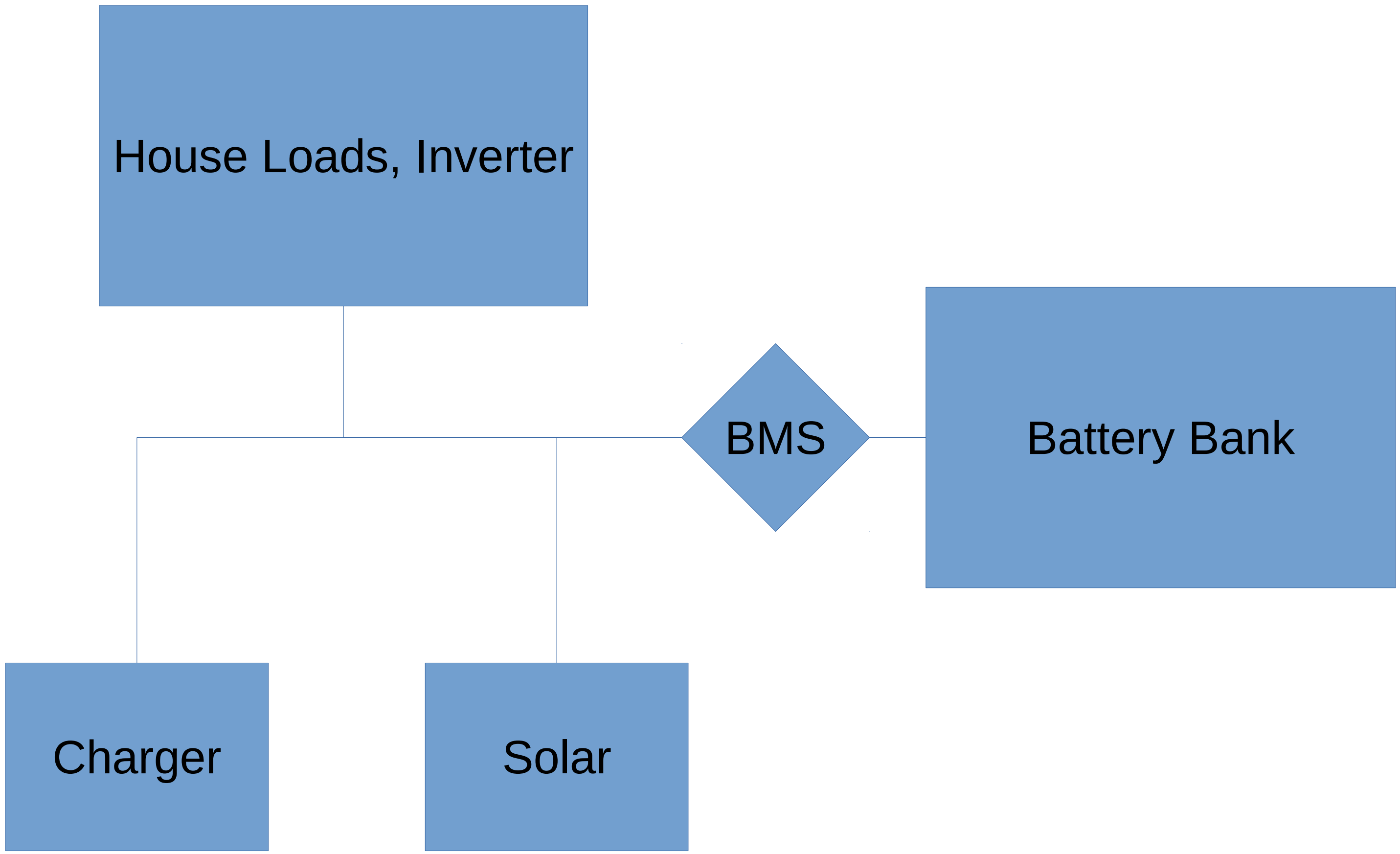
- Lots of energy stored in these batteries, and it's very readily available
- Need to minimize potential for short circuits where there isn't any circuit protection
- Keep things covered as much as possible
- One tool in hand at a time, set tool down before doing anything else.

Preventing Over-Charging and Over-Discharging

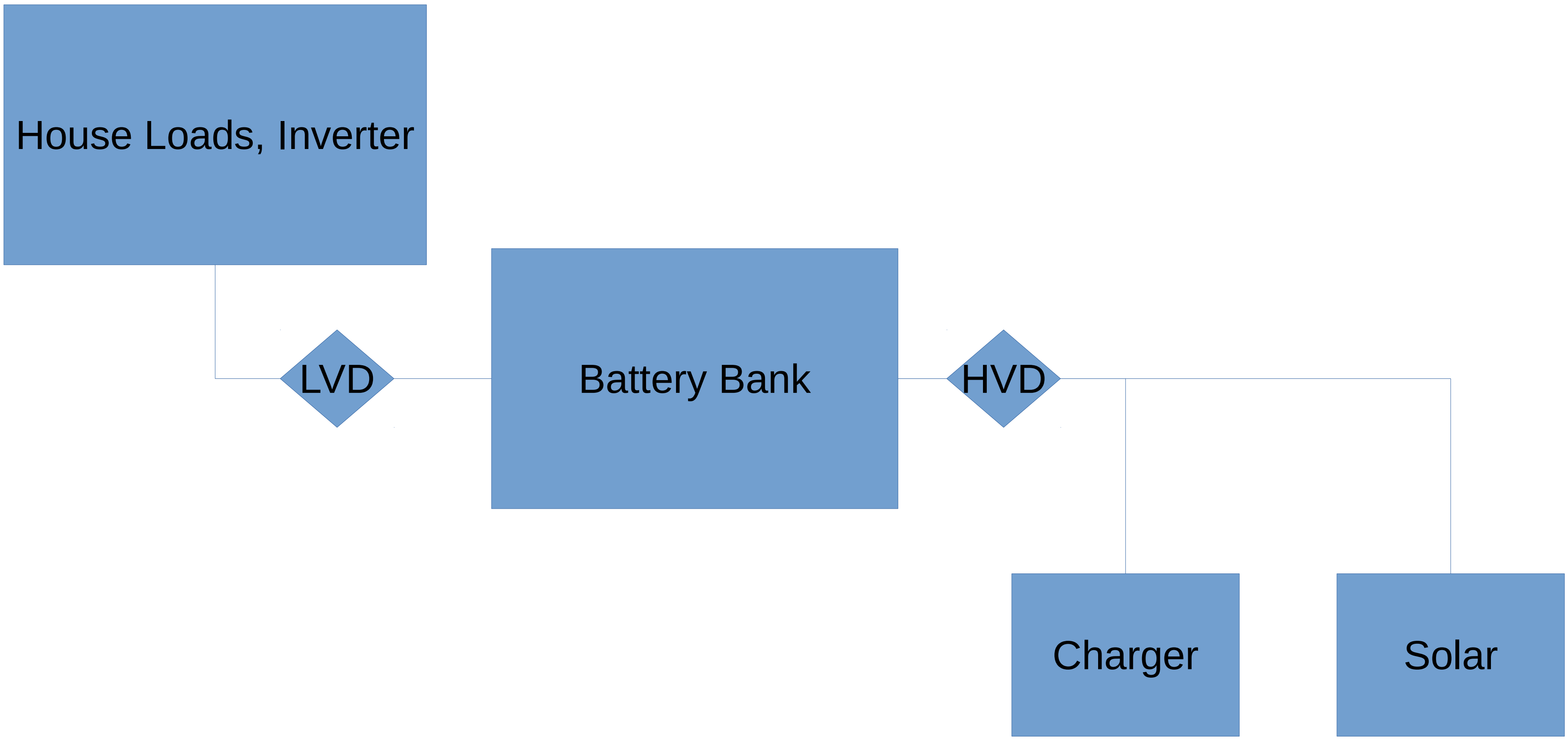
- As a good nuclear engineer (maybe), I want to see independent and redundant means of protecting the battery.
- Inverter's low voltage shutoff is higher by ~4V than where we need to protect battery
- Separate low voltage disconnect interrupts battery feed.

- Need to be able to charge battery when low voltage shutoff is activated

Typical Battery Monitoring System Configuration



What you'd much rather have



Good place for inverter?

- Dead space next to furnace, louvered front panel
- Conditioned space, not too far from batteries
  - Basically in between batteries and power distribution panels
- Inverter fits with reasonable amount of clearance after relocating heater duct

Which Inverter/Charger?

- AIMS 48V 2000W for round one
- 6000W for 20 sec surge rating
- Built-in 20A charger
- Autotransformer
- Transfer switch
- Ground/neutral bonding relay
- Auto generator start
- ~$650, with US-based engineering and support
- Reasonably quiet with automatic fan control
- Handled laser printer, microwave, laptop, ice maker, TVs and dishwasher at the same time
- Simple, but seemingly robust design and construction

Preventing Over-Charging and Over-Discharging

- As a good nuclear engineer (maybe), I want to see independent and redundant means of protecting the battery.
- Inverter's low voltage shutoff is higher by ~4V than where we need to protect battery
- Separate low voltage disconnect interrupts battery feed.
- If charge controller loses power, charging is disabled, but discharging is still permitted.

- Need to be able to charge battery when low voltage shutoff is activated

Observations after Use

- Really pleased with battery performance
  - Under heavy load (>3kW), <0.5V drop
  - Temperature rise during charging ~1 degree
- Cable sizes needed at 48V are much easier to work with than those needed for much smaller systems at 12V
- Even breadboard circuit is still working after 1,000 miles on road
- Ran furnace for 30 mins with duct directly on inverter air intake without overheating
- Nice being able to check on battery status remotely

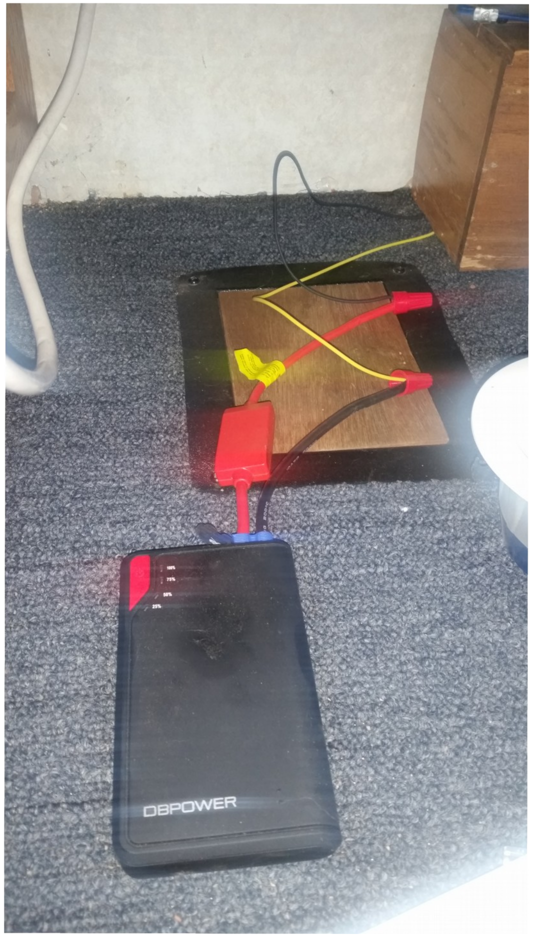
What's next? (From April 2016)

- Bigger inverter
- Stand-alone 12kW charger
- Air conditioner modifications
- Improvements to charger controller
  - User interface
  - Isolation/protection of microcontroller
- Removing 12V batteries and charger
- Connecting generator to chassis (starting) batteries

Removing 12V Batteries

- Need source of 12V power
- Most of the time, 12V loads will be small
  - Water pump <4A
  - Furnace <6A
  - LED lights <<10A total
- But need intermittent power for some big stuff
  - Slide out motor ~30A for <1 min
  - 12V sound system
  - Leveling jacks
  - Starting generator

I cheated.



- Leveling jacks were already configured to operate off of chassis batteries
- Generator should have been configured to start off of chassis batteries
  - Typically, we're starting it because the house batteries need charged…
  - Moved 1 wire, disconnected another to change this.
- Jump starter was able to run slide out motor.
- Currently using 80A converter to run 12V stuff

Reconfiguring Batteries to Start Generator

- Battery separator was located in battery compartment under cab.
- House side cable was moved to chassis batteries, and disconnected beyond generator.
- Now generator is using a battery bank meant for starting, not a deep cycle battery.

“Borrowing” a Battery Section

“Borrowing” a Battery Section

What did I learn from the golf cart project?

- Hard acceleration from the 9kW motor (repeatedly!) doesn’t really get the batteries warm.
  - Why? Even at 10kW, you’re only about 6% of a normal Volt’s peak power.
  - Just 2 2kWh modules (i.e. ¼ of a Volt battery) have no trouble supplying 1000A above safe pack voltages
- Older carts without “soft starting” would be a disaster for a turf maintenance guy

What's next?

- Bigger inverter
- Stand-alone 12kW charger
- Air conditioner modifications

A few other things to consider...

- Not all inverters are created equal.
-

Energy Efficiency has to be Considered

- Most RVs (regardless of brand or price range) are VERY poorly insulated.
- With a lot of boondocking, solar panels can pay off even if never connected (though natural shade would be cheaper)
-

Heat Conduction Basics

$$q'' = \Delta T \frac{k}{x}$$

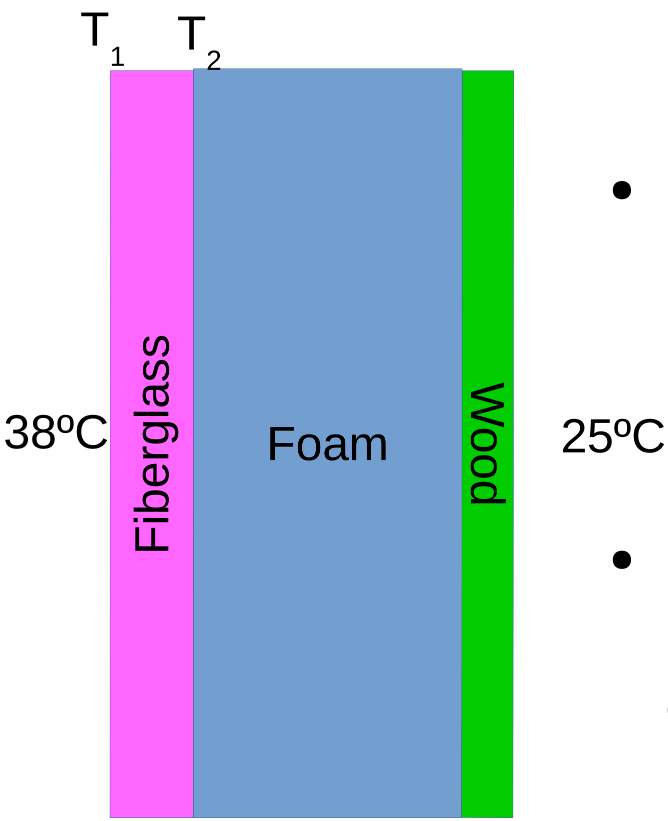
q'' = heat flux (W/m^2)
ΔT = temperature difference (ºC or K)
k = thermal conductivity (W/mK)
x = thickness (m

$$Q = q'' A$$

Q = power (W)
A = area (m^2)

- How is this useful?
  - Look at largest power losses/gains (Q) for improvement. In other words, where Ak/x is largest.
- You can iteratively solve for effective heat gain/loss in a particular environment...
-

Example



- Start at outside wall, guess heat flux.
  - We'll use 25W/m^2
- If fiberglass is 1/16" thick, with conductivity 0.04W/mK, temperature drop with guessed heat flux is:
  - $$T_1 = T_2 - q''\frac{x}{k} = 38\,C - (25\,W/m^2)\frac{(0.0015875\,m)}{(0.04\,W/mK)} = 37\,C$$
- Continue through each material. You'll end up with a different inside wall temperature than what you're measuring. Adjust heat flux and recalculate.

What about solar gains?

- Solar gains change the boundary condition, i.e. the outside surface temperature (not considering windows)
- I will circulate a spreadsheet that includes solar gains, and the effect of shade from solar panels.