An Approach to Lithium-Ion Battery System Design

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Deep Space Lighting

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~~
  - After striking this from the list, I've added it back
- 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)

Sources of Used Lithium Ion Batteries

- Chevy Volt
  - Most readily available
  - Most are gently used (PHEV)
  - Easy to configure for 48V use
- Nissan Leaf
- Tesla Model S, X
  - Expensive, but very large packs
- Fiat 500e
  - Modules are 5 or 6-cell
- Ford C-Max/Fusion Energi

- Other “compliance cars” are much lower in production volume
  - Spark, Focus, etc.

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.

Charging from Truck Alternator

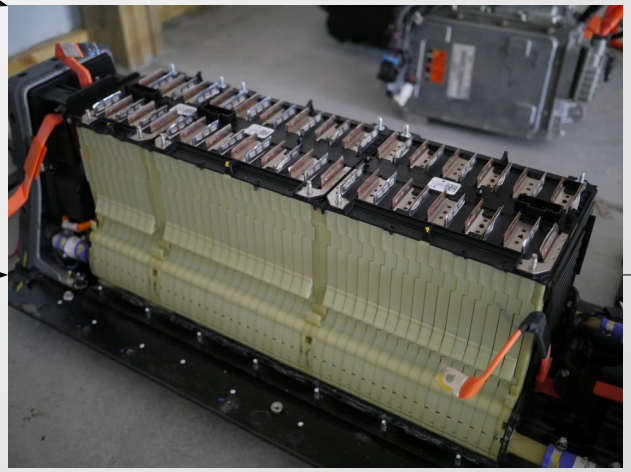
- Not all that much power can be expected
  - Typical 160A (peak) alternator outputs <2kW, and still has to run truck systems
- Need to step up to 48V battery voltage
- Need to limit current drawn from 12V system

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



120V AC Loads

12V DC Loads

Buying the Battery

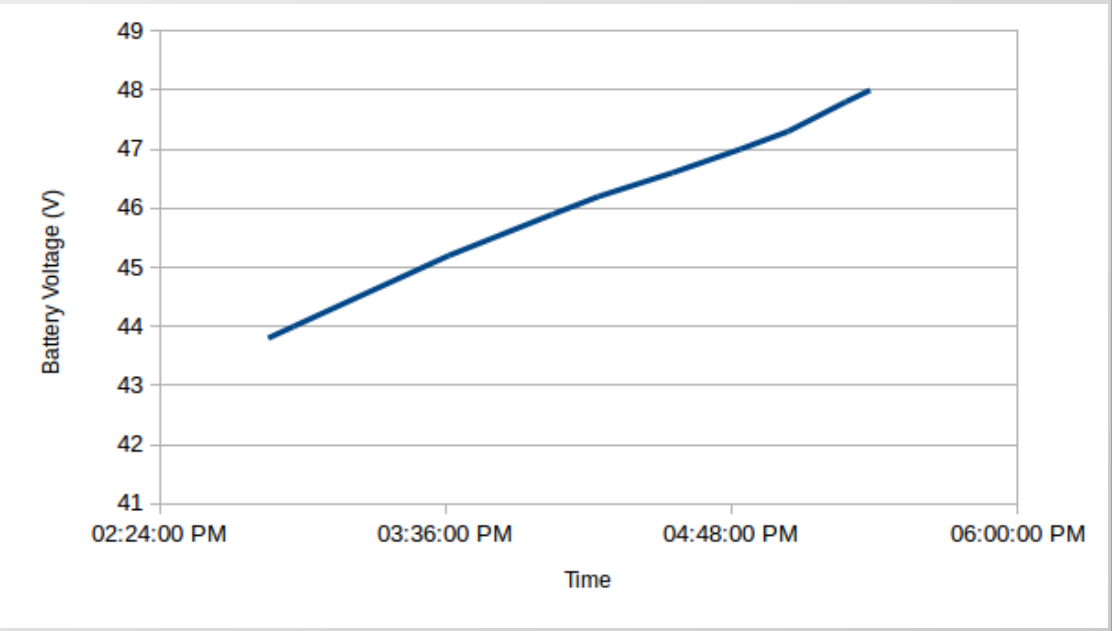
- There are several databases of junk yards where you can find parts inventory.
- Cheapest battery pack in the country when I started looking was less than 15 miles away, so I went to take a look.
  - It was being stored on a pallet outside, and the yard wouldn't budge on a $400 core charge. Pass.
- As of now, there are quite a few used Volt batteries <$1000. Considering that's about 25 T105s worth of capacity, quite a bargain over FLA or AGM.

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.

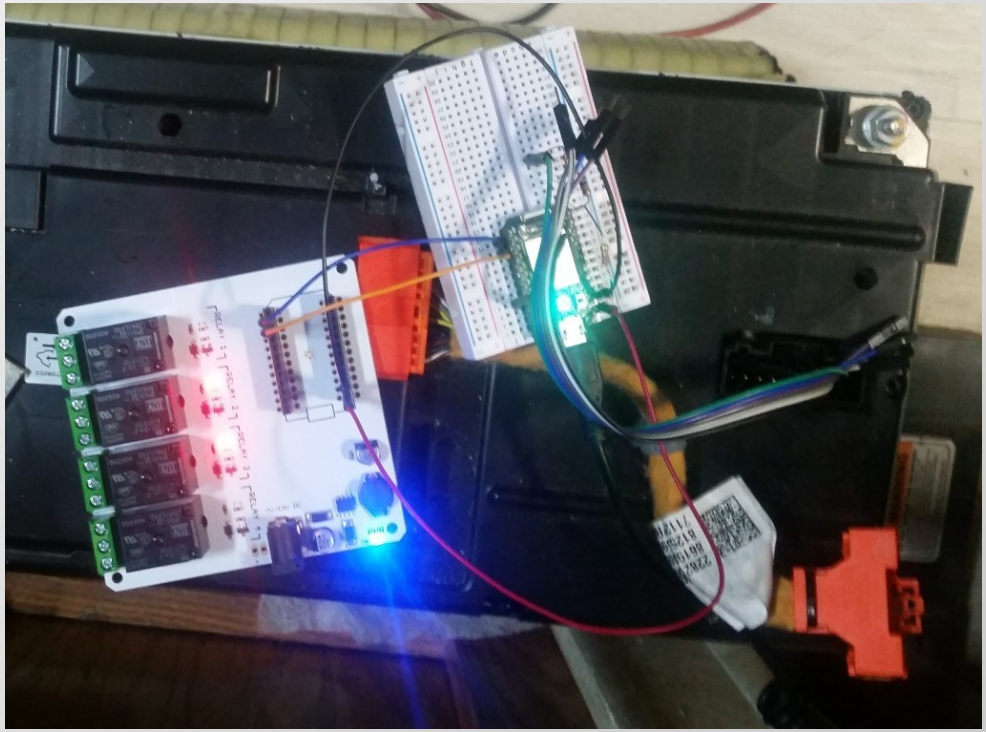
Charging Exercise

- 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



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
- 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, with the top of the T disconnected at the coolant manifold.
- 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.

Fire Safety

- Biggest enemy is heat, regardless of source
- High temperatures can cause charge separators to fail, essentially causing the battery to dissipate all of its energy as heat
- A fire involving lithium batteries doesn't need atmospheric oxygen
- Conventional fire extinguishers are ineffective, and only useful for limiting fire once it has spread beyond battery.
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- Any lithium battery fire should be approached with as much water as possible.
- The goal is to limit heat transfer from one cell to the next, and prevent fire from spreading to other things.

Despite Prominence, Fires are Rare

- Out of 2,128 hybrid and battery electric Toyotas flooded at a marine terminal during Hurricane Sandy, 3 vehicles experienced fires.
  - 16 Fisker Karmas also burned at same location
- Lithium batteries were determined not to be the cause with the Karmas
  - Its 12V battery system and a control module caught fire
- Toyota's investigation just said saltwater was the cause.

- Thousands of vehicles are involved in collisions and returned to service with no inspection or teardown of battery.

Tesla's Guide for First Responders

FIREFIGHTING

Extinguish small fires, that do not involve the high voltage battery, using a CO_2 or ABC extinguisher.

During overhaul, do not make contact with any high voltage component. Always use insulated tools for overhaul.

Stored gas inflation cylinders, gas struts, and other components can result in a boiling liquid expanding vapor explosion (BLEVE) in extreme temperatures. Perform an adequate "knock down" on the fire before entering the incident's "hot zone."

If the high voltage battery becomes involved in fire or is bent, twisted, damaged, or breached in any way, or if you suspect that the battery is heating, use large amounts of water to cool the battery. DO NOT extinguish fire with a small amount of water. Always establish or request an additional water supply.

Battery fires can take up to 24 hours to fully extinguish. Consider allowing the vehicle to burn while protecting exposures.

Use a thermal imaging camera to ensure the high voltage battery is completely cooled before leaving the incident. If a thermal imaging camera is not available, you must monitor the battery for re-ignition. Smoke indicates that the battery is still heating. Do not release the vehicle to second responders until there has been no sign of smoke from the battery for at least one hour.

Always advise second responders (law enforcement, tow personnel) that there is a risk of the battery re-igniting. After a Model S has been involved in a submersion, fire, or a collision that has compromised the high voltage battery, always store it in an open area with no exposures within 50 feet.

HIGH VOLTAGE BATTERY - FIRE DAMAGE

A burning or heating battery releases toxic vapors. These vapors include sulfuric acid, oxides of carbon, nickel, aluminum, lithium, copper, and cobalt. Responders should wear full personal protective equipment (PPE), including self-contained breathing apparatus (SCBA), and take appropriate measures to protect civilians downwind from the incident. Use fog streams or positive pressure ventilation (PPV) fans to direct vapors.

The high voltage battery consists of lithium-ion cells. These are considered dry cell batteries. If damaged, only a small amount of battery fluid can leak. Lithium-ion battery fluid is clear in color.

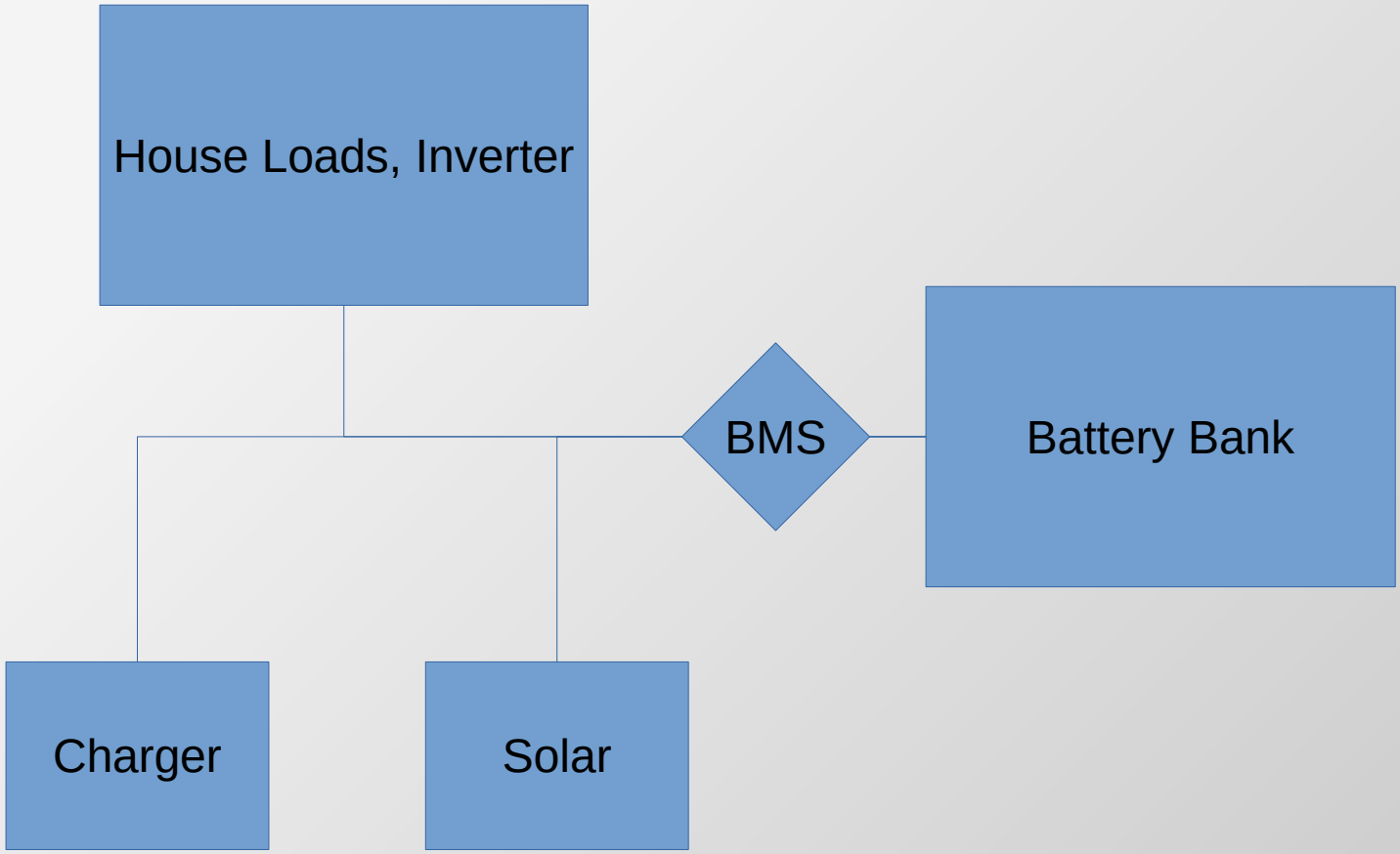
The high voltage battery, the drive unit, the charge controllers, and the DC-DC converter are liquid cooled with typical glycol-based coolant. If damaged, blue fluid can leak out of the battery.

A damaged high voltage battery can cause rapid heating of the battery cells. If you notice smoke coming from the battery area, assume the battery is heating and take appropriate action as described under the heading "FIREFIGHTING" on this page.

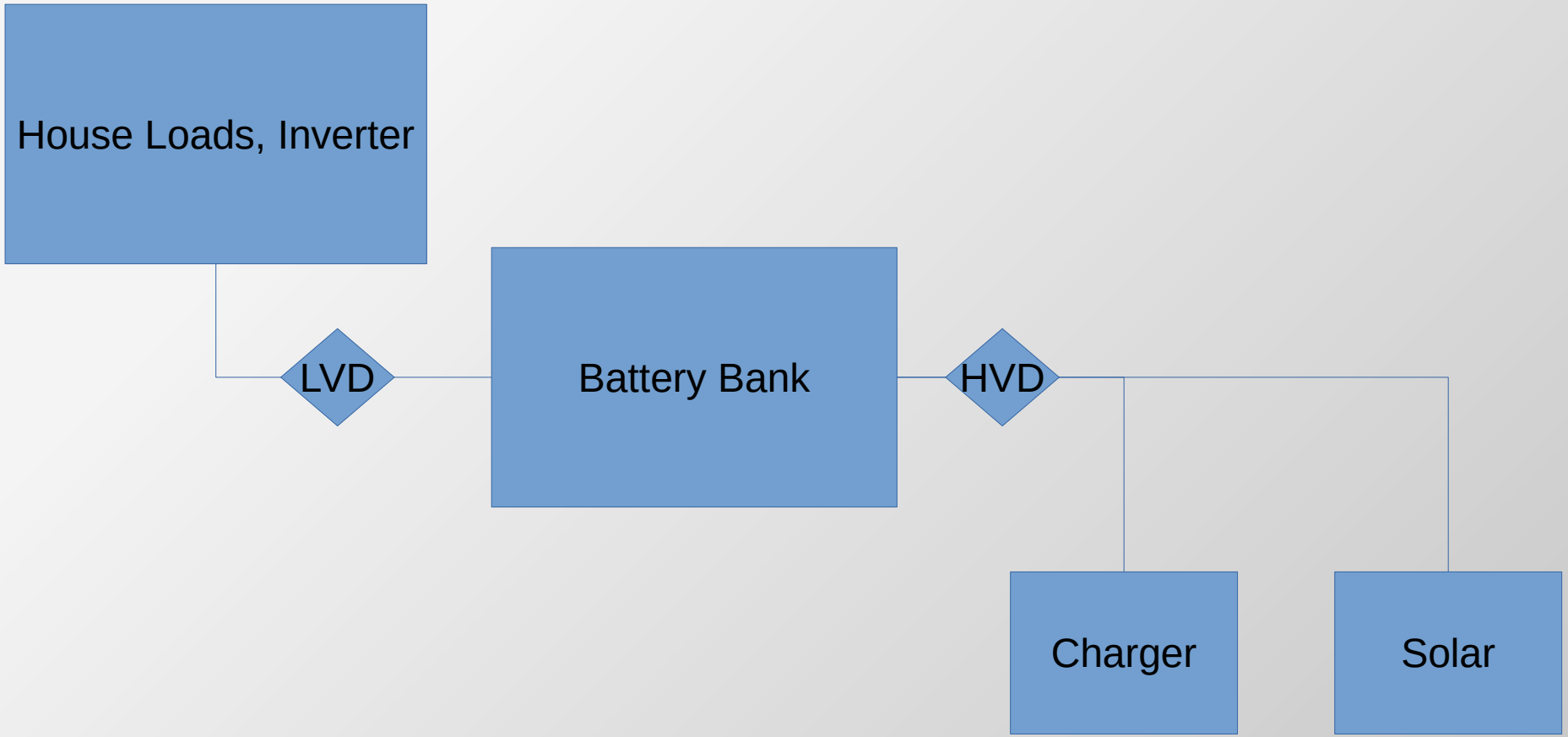
WARNING: When fire is involved, consider the entire vehicle energized and DO NOT TOUCH any part of the vehicle. Always wear full PPE, including SCBA.

WARNING: Regardless of the disabling procedure you use, ALWAYS ASSUME THAT ALL HIGH VOLTAGE COMPONENTS ARE ENERGIZED! Cutting, crushing or touching high voltage components can result in serious injury or death.

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

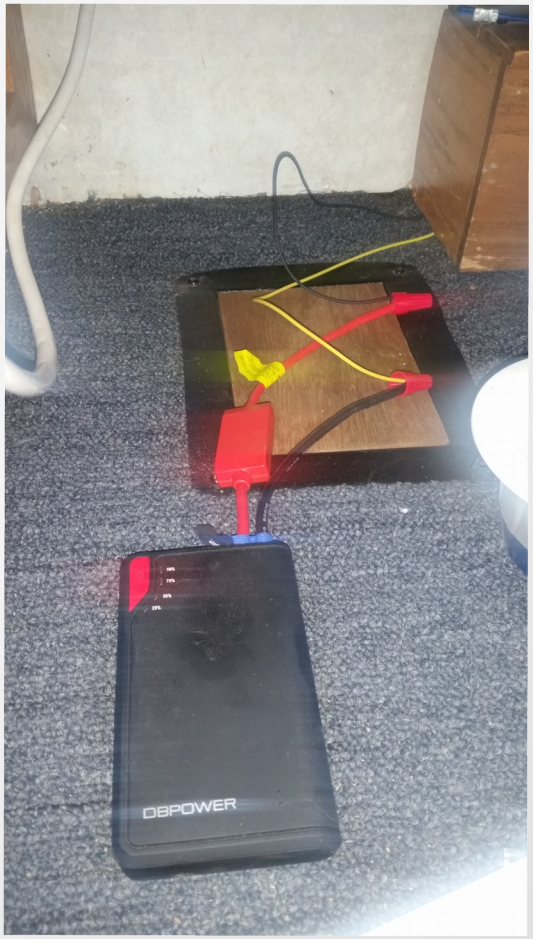
Downsides to Inverter

- Non-programmable shutoff at 40.0V
  - Not a big deal, but could go lower
- Low voltage alarm starts at 42.0V
  - Not a big deal, except:
- Low voltage alarm continues until above 44.0V
  - Basically, have to add 25% charge before it silences.
- Very little diagnostic information/monitoring

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

I really cheated.

- In tracing wires, I found that I could deliver power to just the slide out from the chassis batteries.
- No extra equipment—if the truck will start, I can open/close slide out.

“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

Energy Efficiency has to be Considered

- Most RVs (regardless of brand or price range) are VERY poorly insulated.
- Typical RV air conditioners are very inefficient by modern standards.
- With a lot of boondocking, solar panels can pay off even if never connected (though natural shade would be cheaper)
- The goal isn't an over-the-top battery system—it's extended boondocking without compromises in comfort or a giant hole in the wallet.

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, but pretty uninteresting after a while

Observations after Use

- Much better suited to boondocking
- Charge rates allowed alternating use of one air conditioner and charger on 15A
- One 300W solar panel was enough to keep up with refrigerator and various house loads with no hookups
- Inverter only gets to low voltage alarm after bedtime

Observations after Use

- Two battery sections without metal end plates experienced some swelling
  - May be related to high temperatures or overdischarge

Observations after Use

- Two battery sections were stored for 6 months in unconditioned space.
  - Temperatures well below zero
- Even after storage, pack voltage was right where it was before, with no degradation in capacity.

Observations after Use

- There's a lot more to choose from now than in 2015.
- Volt's battery controllers have been reverse engineered
  - Relatively simple to use factory battery monitoring/balancing functions

Starting over?

- Ford's battery system is air cooled (using a fan), and probably better suited to RV use
- Configurable cell arrangements
- A more "square" form factor, with a more robust enclosure
- Look for some experience with these packs next time around.

Questions?