Design Options for High Power DC Generation

I. INTRODUCTION

I'm designing a completely new adventure truck (Maximus 2.0), and based on the high-capacity systems I already have in Maximus (1.0), I want to change some base elements in the new build. Specifically, I want to move from a '24V' electrical system to a '48V one so I can operate a '48V' mini-split heat pump directly. This will also necessitate incorporating 4-5kW$_e$ of alternator charging capacity. A lot of investigation needs to occur to make this a reality, including developing an entire power system specification. The length and breadth of this analysis border on a manifesto. The thoughts developed here are a compilation of the questions I ask myself and the calculations derived from those questions. I also acknowledge following some tangents.

I believe my goals broadly align with desires existing within the 'self-sustaining' adventure rig segment of the RV community. When setting goals for my future systems, it's worth looking at what the RV industry is doing with DC power systems and what the residential solar industry is doing. I am specifically looking for solutions that can be integrated into a single larger system and not create a patchwork of equipment.

The demand for increased electrical capacity in RVs has been rising and isn't likely to decline. I don't think I'm any different. If anything, I'm more demanding. I think user desire is mainly driven by increasingly larger lithium battery banks that provide access to more energy than ever before. Simply having large electricity storage is not enough to create an effective system. Storage and generation must work together to deliver large amounts of energy, sustainably. Storage is only a bridge between generation and consumption. To use more electricity, RVs need to generate far more than they have in the past. They also need that capacity to be reliable, without a lot of additional labor or manual control.

The 'holy grail' of a self-sustaining RV power system is one that will sustainably power the whole RV, containing heating, cooling and cooking equipment, especially when disconnected from the grid. While Maximus can do this now in the summer, I want more capacity to operate reliably in the other three seasons. This was part of Maximus' overall power plan and has been relatively successful, but I think I can do better.

Before I get into more detail, I want to recognize that I use a lot of electrical references in this document that may lead to confusion if not defined up front.

- If your knowledge of DC power systems is limited to '12V', take a minute to jump ahead to Appendix A – 'System Terms/Standards/Notes' to understand how I and the industry are using terms.
- If you only have a basic familiarity with alternators, scanning Appendices C and D before reading this may be illuminating.
- If you are a current user of DC/DC chargers, a thermal load-shedding device should be high on your list for 'alternator preservation'. See Appendix E for load shedding suggestions.

Currently, Maximus gets most of its generation from a solar system producing between 1.5kWh and 6kWh per day with 6-190W$_e$ rated panels. This is enough to meet demand (including A/C) in the summer, but is generally not sufficient the rest of the year. My second alternator (28V/220A) is capable of continuously producing over 3kW$_e$ in cool weather and 2kW$_e$ in hot weather. While this is substantial, it is not enough to offset a battery debt of 10-14kWh from long stays, sustained poor weather, or limited solar generation in winter. I can't always recover the battery deficit in a 2-3 hour drive, which is how I like to limit my moves. Maximus 2.0 will have a different roof layout, permitting more solar panel space, so I expect improvements in solar generation, but there may still be a significant generation shortfall outside the summer months. I also want to improve generation reliability.

Because my new electrical system will be a '48V' system, the higher voltage affords a path to an even more powerful charging solution to augment and back up the solar system. While I may be an 'early

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adopter' of high(er) voltage power systems, I believe other RVers have similar desires, which is why I am documenting my design process.

II. BACKGROUND

Portable and built-in 120VAC generators have been the backbone of RV power systems since the beginning of RVs, often rightfully criticized for their bulk, weight, noise, and unreliability. In the 90s, solar power started supplementing generators, but despite improving efficiency and cost-effectiveness, solar faces the harsh reality that rooftop space will never be large enough to reliably meet an electrical demand that's growing even faster. The rising popularity of smaller RVs, with smaller roofs, worsens the problem, especially when much of the prime roof space is taken up by one or two air conditioners.

In the past 20 years, small, quieter portable inverter generators have made generator use a more acceptable alternative but the setup, theft and fueling issues have remained. More recently, alternator-supported systems using DC/DC chargers have provided another alternative. A key weakness of the expansion of alternator-supported systems is the relatively small generation capacity of 14V alternators and the complete lack of thermal protection from overload. A typical OEM alternator only has an auxiliary capacity (continuous capacity above the base required for vehicle operation) of around $600W_e$. High-capacity alternators can have up to $1{,}500W_e$. Overloading the alternator has become even easier now that 'smart' alternators have forced battery-to-battery chargers into common use. Key problems remain the undesirability of running a vehicle engine at idle for the time needed to recharge a significant battery debt, along with the inherent inefficiency of running a large engine to turn a small 'generator'.

The desire to replace a separate engine/generator with a high-capacity vehicle alternator system has been sought and generally available for some time. However, the complicating reality is that demand for RV electrical power has grown faster than 14V alternator generation capacity. Some hybrid trucks have been a glimmer of hope with substantial generators and batteries producing 120VAC but they only provide that power when the engine is running. Several custom RV/van manufacturers have achieved significant capacity with 48V systems, but they are rare and expensive. Most 48V systems are considered 'niche' and are not readily supported by RV service centers. None seems to be widely adopted.

III. ASSUMPTIONS

The consumption estimating process takes into account prior usage of Maximus 1.0 and expanded intent for Maximus 2.0. Generation must equal or exceed consumption and be balanced by storage over the sort term.

1) Consumption
   - Routine use of the induction cooktop, air fryer, and microwave consumes 2 to 3kWh per day.
   - The combined demand of any two cooking appliances, when operated simultaneously, will not exceed $2.4kW_e$, and a $2kW_e$ low-frequency inverter with real surge capacity should be adequate for short bursts of high power.
   - 120VAC domestic 11.4CuFt refrigerator (repeating what I have now) consumes around 1 kWh per day and runs on a separate ~500W (smaller than my current 800W) always-on inverter.
   - The planned larger cabin and potentially lesser insulation of a composite box may require more than 5kWh per day for air conditioning. (Which is why an R16, 3" XPS foam box with hand-laid fiberglass is under consideration).
   - Heating will be primarily by fuel burning, but excess electrical capacity is highly desired to heat with the heat pump.
   - Other minor daily consumers are estimated to use around 1 kWh.

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- DHW heating will primarily be by engine waste heat (within 12 hours of arrival) and backed up by a fuel-burning 5kW coolant heater (as it is now). DHW heating can also be achieved using excess solar generation, but it's likely not practical other than in the summer.
- Continuous operation of a small inverter to support the refrigerator and incidental loads loses 0.2 kWh per day.

2) Consumption summary
   - Worst-case summer estimate is as high as 10kWh/day.
   - Best case estimate in winter is around 6kWh/day.
3) Solar generation
   - Fixed rooftop solar system with ~ 6-400W_e domestic panels with a theoretical STC capacity of 2.4kW_e and a nominal capacity of 1.8kW_e (inefficiencies of temperature, angle, orientation, soiling, etc.). Configured in 2 strings of 3 panels, each panel being approximately 1m/40" wide x 2m/80" long, arranged in 2 rows on each side of the habitat roof.
   - Summer generation is based on 6 sun hours and may produce as much as 10.8kWh/day.
   - Winter generation is based on 2 sun hours and may only produce 3.6kWh/day
4) Storage
   - The battery system will be 51.2V LFP (spec range: 40V to 58.4V, planned operational range: 44V to 56V).
   - Based on equipment standards, it is likely to be a single 16kWh unit, using 16S with 314Ah cells.
   - Storage capacity alone should be sufficient for 3+ days of abbreviated use (3 days x 5kWh), with no heat-pump operation.

IV. CONCEPT

I believe '48V' power systems, based on vehicle alternator sources, will become the new standard for the RV industry, and the movement has already started. It will likely remain a minor interest by manufacturers across the spectrum of RV Classes for some time. RV manufacturing has always been about producing the lowest-price product, which is gleefully improved with expensive options. Manufacturers are up against the hard reality that the masses can't really afford high performing products, so they are not really about evolving to higher performance standards. The evolution will need to come from 'zealots' who will deal with the 'bleeding edge' until price comes down…..that is the way its always been.

The most unrealized desire is for efficient air conditioning and for it to be available off-grid, which is pacing the need for high(er) power, high(er) voltage DC to achieve it. I don't believe the 'right' system or concept is widely acknowledged by the market but DC residential mini-splits are close. Strong recharging capacity for high(er)-capacity batteries and DC equipment is already in high demand in both the RV and boating communities. High amperage and high associated losses have been recognized in the boating community as obsolete but the RV community continues to hang on. It is unfortunate that '12V' systems are still completely adequate for the vast majority of automobiles. Based on my experience in the RV industry (I was a Class-A plant engineer for 3.5 years), '48V' adoption will only be widely adopted when the cost to do so is nearly equal to '12V'. It will be slow, and without standardization beyond the common voltage. Several reasons are driving this trend;

- High energy delivery needed for DC air conditioning is inefficient, bordering on uneconomical at the high amperages necessary in a '12V' system. To effectively achieve high power delivery, system voltage must increase substantially while still enabling compatibility by supporting '12V' equipment through DC/DC converters.

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- ‘48V’ high-power/high-efficiency alternator systems have been in volume production with ‘mild hybrid’ automobiles (EURO6 standard in effect in the EU since 2014. See Appendix D), demonstrating that OEM automobile manufacturers are proficient with the manufacturing of efficient ‘48V’ generation, storage, and control equipment. Despite a customer interest, the market has not responded in any meaningful way to bring this equipment to the RV industry.
- The residential solar market has embraced ‘48V’ battery systems for battery backup, making ‘48V’ equipment common and cost-effective.
- Standard automotive alternator efficiency is poor, typically ranging from 30-75%, and averaging around 50% at high speed and high output. Said another way, a 50% efficient alternator produces 1 unit of electricity simultaneously with 1 unit of waste heat. Substantial waste heat at low power levels is manageable, but at higher power levels, massive heat generation is uneconomical and overwhelms the alternator’s ability to operate safely.
- ‘Hairpin’ stator alternators have significantly higher efficiency, averaging around 70-75%. At 75% efficiency, the alternator produces 3 units of electricity simultaneously with 1 unit of heat. Because the ratio of heat to electricity is so much higher, hairpin stators have much higher continuous capacities in the same-sized device.
- 56V commodity alternators and external regulators are available for both automotive and marine applications, primarily aimed at supporting 16S LFP battery systems. A 56V alternator can replace or operate in parallel with a 14V alternator. They typically have a rated capacity ranging from 4-8kW_e, providing enough generation to eliminate the need for separate generators and vastly improving battery recharging with short drives.
- Automotive permanent magnet (PM) generators use a 3-phase stator with a permanent magnet rotor. Because the magnetic field is constant, the stator generates a varying frequency and varying voltage AC. Unlike traditional alternators, the variable voltage output is processed by an integrated DC/DC converter to produce a stable DC output voltage. They generate electricity at over 90% efficiency and convert the output to a stable voltage, also at over 90% efficiency, yielding overall generating efficiencies above 85%.
- Australian manufacturer Safiery offers a 56V PM generator that has an integrated DC/DC converter on the back of the alternator, producing a stable 56V output, coupled with an integrated external DC/DC converter and voltage regulator. The external regulator controls the integrated DC/DC converter’s output voltage and the external converter ‘bucks’ some of the 56V output to ‘12V’ or ‘24V’ to support automotive operating requirements (even winches).
- ‘48V’ DC air conditioners with sophisticated variable capacity capability exist in both mini-split residential and to a lesser extent, in mobile models. Using ‘48V’ BLDC motors, they begin achieving theoretical efficiencies at 48V and higher.

There are significant, probably uneconomical, obstacles to the conversion of existing ‘12V’ RV systems to a higher system voltage. Some issues can be mitigated, but I can’t imagine many RVers taking the intellectual deep dive necessary to convert a ‘12V’ RV into a ‘48V’ one, even if it were economical.

- Most existing high-capacity lithium RV battery banks being built from multiple ‘12V’ equivalent batteries can be reconfigured from ‘12V’ to ‘48V’ with only cabling expense if battery compartment space allows multiples of 4 batteries.
- Some large (unlikely most or all) PV systems can similarly be reconfigured to ‘48V’ with new chargers.

- ‘12V’ inverters must be replaced. ‘48V’ inverters exist in quantity and variety, thanks to the residential solar market. They are generally more efficient, less expensive and more capable than typical ‘12V’ models.
- Conversion of ‘12V’ single automotive alternator systems to dual voltage systems is possible but likely difficult and expensive due to the variety of existing automotive engine systems, many of which would violate warranty conditions if modified.
- A ‘warranty work around’ could work if RVs could ADD a second 56V alternator to create a wholly separate power system for the habitat and leave the automotive system alone. This seems the most prudent and likely path. The ability to find equipment to do it and the cost likely vary widely.

I believe, due to the difficulty and cost of conversions, few existing ‘12V’ RVs would be cost-effectively able to be converted to support ‘48V’ systems. This migration would need to be supported on new RV purchases by manufacturers offering an ‘upgraded’ power system when ordered or by DIY builders. There is a much more likely path using option kits to add 56V generation to a wide range of prime movers, such as heavy-duty trucks and chassis (for class-B, class C, trailers and truck campers) many of which are available with factory-installed dual alternator systems. There is currently aftermarket equipment available (although rarely in kit form) to add high-voltage (‘24V’ and ’48V’) alternators to some vehicle models.

V. OBJECTIVES

My concept for Maximus 2.0, starts with a single-cab, F550 with a 7.3l gas engine, mounting a habitat with a 14ft floor/18ft habitat length. I want to have a ‘48V’ electrical system to support a ‘48V’ mini split, so I intend to implement a 56V alternator with around $5kW_e$ capacity. I also prefer a dual alternator solution (my current system) for redundancy. To understand where I got this from, I started by making assumptions about demand, storage, and solar generation, even though those design elements have not been fixed. In general, my high-level goals include;

1) Power the heat pump with DC to eliminate the need for long-term operation of the main inverter. Use a ‘48V’ power system and a ‘48V’ mini split heat pump. If not for my heat pump, the main inverter would usually operate less than 30 minutes per day at an efficient >50% load for cooking appliances.
2) Using a large inverter for small loads is inefficient. The graphic below represents the relative efficiency of different inverter designs. Assume high-efficiency inverters are necessarily purpose-specific and not available for general use. Medium efficiency is where most of the general-purpose, name-brand, pure sine designs (like those used in RVs) operate. Low efficiency is generally associated with older, less capable designs, like ‘cheap Chinese’ models. Most inverter manufacturers rate inverters as being ‘93% efficient’, and I’m sure they are at some point on their power curve but what they don’t tell you is that ALL of them are INEFFICIENT at low power levels. The key takeaway is to size the load (s) to the inverter so that you always operate above 30% capacity. Don’t get a ‘too big’ inverter, thinking its better to have excess capacity and don’t run any load for a long duration.

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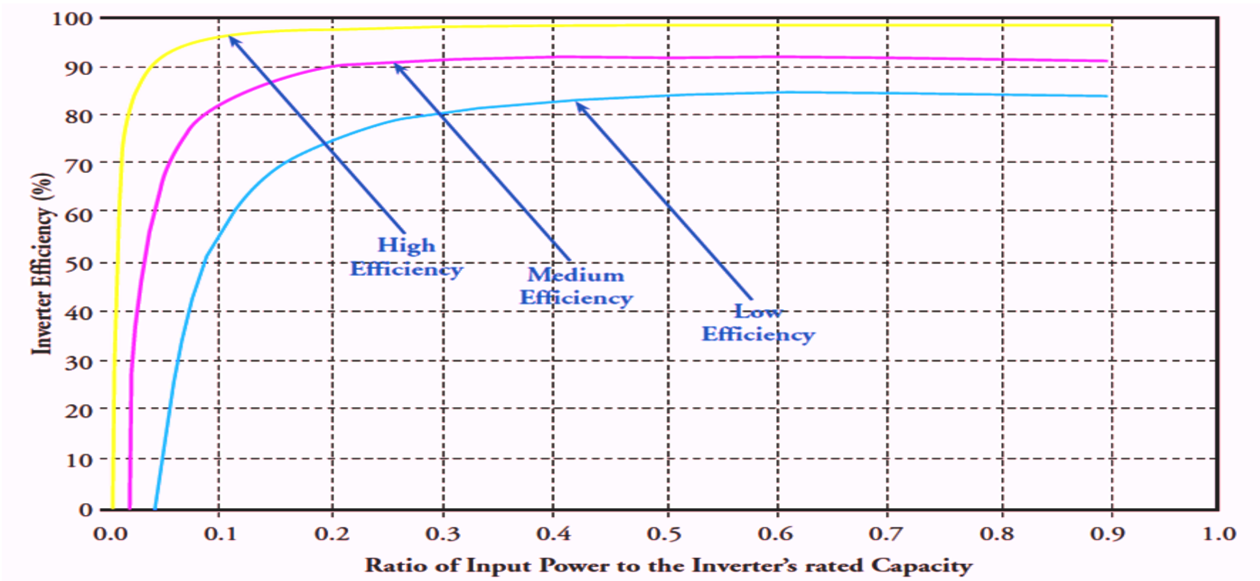

Figure 1: Inverter Efficiency vs. Load

3) Operate a second, ~500W_e inverter ~16 (hrs)/7(days) to support a residential refrigerator and small loads in the camper. I assume I can operate the inverter full-time during the day and intermittently during the night to save on consumption. Since nights are cool(er) and the power would have been on all day to bring the refrigerator to a stable temperature. I will use an automatic interval timer to shut off the inverter several times for 2-3 hours at night without significantly disrupting refrigerator temperature. There are a couple of potential shortcomings;
   - The use of a 120VAC mattress pad heater during winter nights. While it will be on in the evening to support pre-warming the bed, automatic shut off during sleeping hours for longer durations may be sub-optimal. If this becomes an issue, shifting to more frequent intervals with shorter off durations, to provide more frequent heat, may be adequate.
   - Charging personal electronics at night is the norm. I currently use 120VAC-powered USB supplies, which would be affected. For Maximus 2.0, I will use a '48V' to USB DC/DC power supplies.
4) Reduce the size of the inverter to ~2kW_e and make use of the real 'surge capacity' of a low-frequency inverter to achieve ~2.8kW_e of short-term power. A low frequency, low(er) power, 2kW_e inverter is desirable to make use of its 'real' surge capacity that will last several minutes to support simultaneous operation of the microwave and induction cooktop. This supports the simultaneous use of two cooking appliances.
5) The operation of the microwave is usually at high (maximum) power, but it only lasts for a few minutes. This requires the full power capacity of the microwave to always be available from the inverter.
6) Using the induction cooktop RARELY draws full power unless using 'speed boil' (rare). Most of the time, it is at half power or less but draws power in pulses.
7) The combination of these two factors means that both appliances nominally rated around 1500-1,800W_e CAN THEORETICALLY require 3000W_e+ to operate both at full power but usually, they do not operate at maximum or for long, so could operate simultaneously with an inverter with a 2000W_e continuous capacity that also had a REAL surge capacity of 20-40% (2,400W_e-2,800W_e) for several minutes, which low frequency inverters do.
8) I still want equal or increased power system capacity than Maximus 1.0, which includes:

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- 1,140W_e (STC) of '24V' solar panels that produce 1.5-6kWh/day
- 17.5kWh of 24V lithium battery
- .8kW_e and 4kW_e inverters
- 9kBTU/120VAC mini-split heat pump
- Backup power with dual alternators. 14V/135A primary alternator and 28V/220A on-demand (not always on) second alternator.

9) Initial targets for Maximus 2.0 systems:
   - Primary generation of 2,400W_e (STC) solar producing 2.7-10.8kWh/day
   - 16kWh of 314Ah/16S (51.2V) LFP battery
   - .5 and 2kW_e/120VAC inverters
   - 12kBTU/'48V' mini-split heat pump
   - Backup power with dual alternators, the secondary being 14V/250A for the truck/winch, primary 56V/4-5kW_e+ on-demand alternator solely for the habitat.
10) The backup power system must have the capacity to be a long-term, sole source with no solar contribution. Since I have experienced 2 separate failures of my solar system, I feel this is essential.
11) Buying a large LFP battery is almost as cheap as building your own. Use a commodity 16S LFP/51.2V battery and power equipment that is readily available in the solar market to keep costs down and increase flexibility.

VI. ANALYSIS OF OBJECTIVES

1) Solar Generation Deficit: The result of the consumption and solar generation estimate yields a frequent energy deficit that can range up to 2.4kWh/day under good conditions with no buffer for loss of generation or abnormal consumption.
2) Deficit Effect
   - The summer, being the highest solar generation season but also the highest consumption season, will periodically experience cloud cover, resulting in less than optimal generation. ANY shortfall will either increase battery debt or require a lower operational level.
   - With the best case, near net zero generation/consumption, any abnormal demand or weather/seasonal loss of solar generation will lead to a storage debt that can only be replenished by alternative generation. This is most likely to be a larger problem in the winter season, but it can occur at any time.
   - It is possible that a battery debt of 10-12kWh can accumulate in somewhere between 4 days and a week of operation. While this is far longer than my usual stay interval, I have been stationary for this long before, and want to be able to operate on this cycle comfortably.
   - Based on a planned battery operating capacity of 14kWh (operating from 56V-95% SOC to 44V-5% SOC), the battery alone can be assumed to provide 5 days of reserve capacity with at least minimum solar generation (14kWh battery capacity – 2.5kWh/day deficit = 5.6 days) in the winter.
   - I therefore surmise that alternative generation is likely always going to be desired to be 'readily available AND reliable. 'Power anxiety' is real and can be mitigated by a strong reserve capacity.
   - An 80—90% battery debt (~12kWh) could ideally be recovered in under 3 hours of driving. This requires a generation capacity of more than 4kW_e, at any ambient temperature.
3) Generation Alternatives
   - Powerful short-term sources, such as a vehicle alternator or portable generator.

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- Moderate long-term sources are likely restricted only to portable solar. While wind power is a frequent suggestion. I feel wind conditions able to provide sufficient generation are both rare and HIGHLY undesirable in which to camp. If I were in a location that had sufficient wind to support a wind generator, I would not want to stay there.

4) Generation Labor/Reliability Factors
   - Alternator Generation
     - No setup, storage or maintenance required
     - Always, instantly available
     - At least as reliable as any other vehicle alternator (high)
     - Practically more powerful than any other alternative.
   - Portable Generators
     - Reliable production unaffected by environmental conditions.
     - Long-term reliability of small engines is not high.
     - Significant setup/recovery effort.
     - Require an additional fuel container to be carried, stored, and periodically refilled.
     - Is a theft target and needs to be put away whenever leaving the campsite, increasing the labor requirement. Because I have a tow vehicle, I plan to leave the campsite unattended regularly.
     - Is not easy to store immediately after operation.
     - Fuel spills in storage are a concern.
     - Requires periodic maintenance. Failure to do so affects reliability
   - Portable Solar
     - Needs to be large
     - Requires significant storage space
     - Needs to be manually erected, probably also reoriented several times throughout the day.
     - Must be recovered prior to moving and possibly every time leaving the campsite for the day (theft).
     - Subject to the same solar/weather problems as the fixed array.
5) Sizing Alternative Generation. The size of the alternative generation needed warrants some estimation. With an already calculated 2.5kWh maximum daily deficit, to recover that debt (12kWh max), would require:
   - Portable Generator: Average daily operation of a 2kW$_e$ generator for 2.5 hours at 50% load (.5l/hr, to maximize fuel efficiency).
   - Vehicle Alternator: Operation of a high-capacity (5kW$_e$+) vehicle alternator for 2 hours every 4-7 days.
   - Portable Solar: Around 1600 STC watts of portable solar panel (producing 1,200 nominal watts) erected every day in winter (collecting 2 sun hours) or every 2nd or 3rd day in summer (6 sun hours).

Summary: This calculation virtually disqualifies portable solar from consideration. Generation capacity is so low in the winter that it would require a huge system, requiring considerable labor to set up, and still lack reliability. While it’s likely that the portable solar system can be permanently stored away in the summer, the purpose of this investigation is focused on reliable capacity year-round.

6) While a portable generator is still an option, I dislike the frequent amount of operation it requires, the theft risk, and the storage/setup labor.

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Summary: For the way I want to travel/operate, storage space and setup/recovery are large negative factors, particularly when compounded by near-daily side trips in the tow vehicle. I´ve ignored cost comparison because I feel the benefits of the most effective solution will outweigh the cost differential over the long term. The labor involved in using portable solutions, the perceived unreliability, and the apprehension of theft take a lot of the enjoyment out of the camping experience, making it unfavorable when alternatives exist. That being the case, I am only proceeding from here with a more in-depth analysis of alternator solutions.

7) See in-depth discussion of alternator capabilities in 'Appendix C: Alternator Design/Operation.'
8) Alternator 'types'. 'Standard' automotive alternators are sold as two different types; fixed voltage or variable voltage (aka 'Smart' alternators). The alternators are mechanically identical. They only vary by the type of internal voltage regulator used.
    - Fixed voltage regulators are not precisely fixed; they operate within a small voltage range based on temperature. They have a small negative temperature compensation to prevent overcharging of hot lead-acid batteries, caused by high under-hood temperatures. Typical output is 14.1-14.2V when cold, tapering to ~13.8V when warm.
    - Variable voltage regulators are actually fixed voltage regulators that can accept external commands to change the setpoint voltage, typically ranging from 12.4V to 15.5V. Engine Control Units (ECU) are in direct communication with the alternator 'GenCom' port. When the Body Control Unit (BCU) senses increased loads (caused by a voltage drop from additional power draw or by specific equipment being used), it requests the ECU to pass a 'command' to the regulator to increase the output voltage. The ECU monitors feedback from the voltage regulator on the 'GenMon' (monitor) port. The 'GenMon' signal is the duty cycle being used by the regulator to achieve the setpoint voltage. Duty cycle is a percentage measure of the 'on' duration of the excitation power sent into the rotor. A higher duty cycle is a measure of the effort required to support the requested voltage.
    - A variable voltage alternator can be turned into a manually controlled, fixed voltage alternator by bypassing the ECU communication to GenCom, using a small '12V' to 5V (~$3) DC/DC converter operating a variable PWM signal generator (~$10), outputting a 126Hz pulse width signal to mimic the ECU command sent on GenCom. While this seems complex, it is actually very simple.
    - Automobiles have a constant need for generated electricity. They can only sustain operation for a short time from stored (battery) electricity. No internal regulator can reduce or stop output based on elevated temperature. They are intentionally designed to operate till failure because of the priority for mobility of the automobile. If a user puts too much load on an alternator, it will produce to its maximum ability till failure.
9) There are two active methods to prevent overheat-induced failure;
    - Reduce Excitation: Lowering the duty cycle of rotor current reduces the strength of the electromagnet, thereby reducing output voltage. If a load draws power based on Ohm's law (resistive), power consumption will be reduced (such as direct battery charging).
        - Using an external regulator with a temperature sensor will reduce excitation as the alternator approaches maximum temperature.
        - Electronic loads such as DC/DC chargers respond to the reduction of output voltage by <u>increasing</u> current draw to <u>maintain</u> the same input power so reducing excitation does result in reduced load.
    - 'Load Shedding': Disconnect/reconnect auxiliary loads based on temperature thresholds. For large loads such as auxiliary lithium battery charging through a DC/DC charger, duty cycle

reduction alone will not reduce power draw. An alternate method to disconnect the auxiliary load from the alternator's power network is necessary to protect the alternator;

- Use an external regulator with an 'unloader' function (ARCO Zeus) that can control either a cutoff relay or trigger the device to shut down, such as by shutting off the '12V' signal to the ignition sense lead on a DC/DC charger. Disconnecting power cabling with a relay causes a 'harsh' disconnect that WILL cause a voltage spike in the alternator that gets larger under higher loads. It is preferable to initiate a 'shutdown' of a device rather than cut it's power off. A regulator's unloader function is programmable for activation/reset temperatures and duration.
- Use a KSD-9700 thermal switch (Normally Closed, 120C activation) epoxied to the alternator case that activates at a fixed temperature to either open a cutoff relay (unintelligent device) or shut down an intelligent device through the ignition sense lead. Reset is typically 10-15C lower than activation. This is very simple and inexpensive, but not adjustable.
- Mount an industrial temperature controller in the cab with a temperature sensor (Type K thermocouple) attached to the alternator case to either open a cutoff relay or shut down a device with an ignition sense lead. This costs less than $100 and is not only adjustable for both activation and reset, but also displays the current temperature.

➢ External regulators have a variety of optional sensors and programmability to optimize generation. They use alternator temperature sensing and current sensing to maximize output while attempting to manage alternator temperature with varying excitation. As stated above, simply reducing excitation, resulting in reduced output voltage, may not reduce loading if electronic loads are present.

➢ Different regulation strategies exist, and they are often used in combination. Primary among them are;

- At startup, excitation starts low and ramps up slowly to limit engine load, preventing rough idle during warmup.
- Diesel engines using 11V glow plugs are very susceptible to elevated voltage damage by high-capacity generation. 'Standard' alternators at idle have 60-100A capacity. With glow plugs operating and battery debt being replaced, they are incapable of raising system voltage above ~13V. During warm-up, the ECU in dual alternator-equipped trucks 'locks out' operation of the second alternator for the first 2-3 minutes after start when the glow plugs are still cycling. Replacing the primary alternator with a 'high output' alternator capable of 200A+ at startup results in much higher system voltage immediately after startup that can burn out glow plugs. Using an external regulator allows programming an extended length voltage ramp up to avoid harming glow plugs.
- After some warm-up, the excitation ramps up to recoup the starting debt.
- At all times, alternator temperature is monitored to prevent overheating. If high loads cause the alternator temperature to approach the maximum, the regulator will lower excitation to reduce alternator output voltage, expecting to correspondingly reduce output current. This can have negative consequences for electronic fuel injection systems if the system voltage gets too low.
- Sailboats, having smallish engines, may need to prioritize the limited power for thrust at some times and for generation in others. Max or min generation scenarios can be set. Similar needs can be implemented for heavily loaded trucks when hill climbing or passing.

➢ Different brand regulators have different numbers and types of sensor inputs and control outputs.

- Wakespeed WS500 regulator has;
  a) 1 alternator current sensor
  b) 1 alternator temperature sensor

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c) Bluetooth programmability

- ARCO Zeus regulator has;

a) 'Load shedding' capability, implemented by a separate signal lead that can command a shut-off of external loads based on programmable criteria.

b) Dual current sensors, one for the alternator and one for the auxiliary battery. They provide additional input to enable more sophisticated programming. This allows the alternator to sense how much current is going to loads and how much to battery charging.

c) Dual temperature sensors, one for the alternator to take action in the event of alternator over-temperature and one for the auxiliary lithium battery to prevent charging during over- or under-temperature events.

d) Bluetooth programming and a robust monitoring app.

- Balmar MC-620 regulator has;

a) Programmability through an embedded magnetic contact (klunky)

b) 1 battery temperature sensor

c) 1 alternator temperature sensor

d) Current sensing can only be done with the addition of the Balmar intelligent shunt and intelligent battery monitor (both).

e) Bluetooth programmability can be added with a Bluetooth dongle (option for the intelligent battery monitor).

10) Constraint-based electrical system design;

➢ Maximum Case: At times, battery debt will be significant (10-14Kwh) and require powerful and reliable alternatives to recover, at least a majority of the debt, in a reasonable period. I define ´reasonable' to be no more than 3 hours because I want to achieve a nearly full charge in my drive time between sites. This sets a maximum continuous capacity at around $5kW_e$.

➢ Minimum Case: Because I rarely stay more than 3 days in one place (3 days x 2.5kWh daily deficit) my average debt is likely to be around 7.5kWh. This would require $3.75kW_e$ continuous capacity on a two-hour drive.

➢ Applying a waste heat limitation of $1.5kW_t$ (the upper limit), the generation limit at 75% efficiency is $4.5kW_e$. This confirms that a high-efficiency hairpin alternator is minimally acceptable.

➢ Planning to operate at the thermal limit of the alternator requires sophisticated control to prevent failure. The control system must be able to maintain stable generation and prevent thermal overload. This requires sensing output current and alternator temperature to compensate for varying load and environmental conditions. Sensing of battery temperature and external loads being supplied is desirable.

➢ If control parameters cannot maintain regulation within desired maximums, automatic load shedding must be available.

VII. SOLUTIONS

I believe that for the rig I want to build, a '48V' system is best powered either directly or indirectly by an alternator. Portable solar panels and generators are too labor- and storage-intensive for my taste. Even before considering a 56V alternator for a high-power system, the important question is whether one or two alternators CAN be used. Not all engines can mount two alternators, and if they can, the available 56V alternators may not be available in the OEM case styles. Due to the presumed waste heat limit of 1.3-$1.5kW_t$, high-capacity alternators will need to be high-efficiency (hairpin or PM) designs to provide continuous high capacity.

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1) For RVs or prime movers wanting to run both ‘12V’ vehicle and ‘48V’ habitat systems, three options exist;
   a. Replace the existing 14V alternator with a 56V alternator, then add a ‘48V’ to 13.8V DC/DC buck converter to support ‘12V’ vehicle systems (the ‘mild hybrid’ model).
   b. Replace the OEM single 14V alternator with a high-output 14V alternator, then add ‘12V’ to ‘48V’ boost converters to support the RV system. Adding boost converters alone provides a similar ‘48V’ capacity for existing OEM dual 14V alternator systems. OEM dual alternator activation is ECU-controlled and may not provide the desired output under all conditions.
   c. Use two alternators, one for each system voltage for the respective power system.
2) Mounting dual alternators for separate power systems seems the most desirable, but dual alternator mounts and drive systems are far from universal. Building them one-off would get extraordinarily complicated and expensive. Assume that if a second alternator design is not already available, any system will need to rely on a single alternator solution.
3) Heavy trucks, which are used as prime movers for Super-C’s, tow trailers or carry truck campers, are much more likely to have factory-designed dual alternator systems. If factory dual mounts are available, dual alternators are a good choice because they can leave the ‘12V’ automotive system intact. Aftermarket brackets are also available to support second alternators for high-power stereo applications in passenger vehicles, but generally don’t extend to larger RV engines. Just having separate alternators is a heat dissipation advantage, with each able to generate a continuous capacity separate from the other. The reliability of a two-alternator system is also appealing.
4) Finding a high-capacity alternator that is an ‘exact fit’ for an OEM-specific mount is possible and improving (see Mechman.com). Using any of the existing 56V marine alternators may require a custom-made mounting adapter. Most 56V alternators currently available seem to have more generic mounts such as J180, 1” and 2” wide hinge ‘foot’, but I am surprised that a large number of GM ‘saddle mount’s are available. The boating community has been into high-output charging alternators for some time and the jump to ‘48V’ systems seems to be widely embraced. In particular, the boating suppliers are almost exclusively the developers of advanced external regulators (Balmar, Wakespeed and ARCO in particular).
5) Maximus, built on a 2004 F350 with 6.0l diesel, uses a modified 4G Ford second alternator and external regulator to create a ‘24V’ system for most of the reasons above. I expect that Maximus 2.0 will use a second 56V alternator mounted with an OEM dual alternator drive on a Ford F550 w/ 7.3 gas engine. That is not to say I have conclusively decided to use 2 alternators; I will keep an open mind to single alternator systems as the equipment options are investigated.

VIII. SYSTEM ARCHITECTURE

Adding a high-power alternator adds a lot of demand on an engine. OEM dual alternator mechanical drive systems are designed for alternators that may each produce ~14V/250A@60% = 3.5kW$_e$ peak/2.1kW$_e$ continuously. They may use one drive belt or two. Before adding or substituting a 56V alternator that can quadruple the required drive power, its worth considering the effect.

Adding a ‘48V’ alternator that can produce a 5kW$_e$ output at approximately 75% efficiency will require about (5kW$_e$/0.75 =) 6.7kW or 8.9HP from the accessory drive belt. This is between two and four times the mechanical power needed by an OEM single alternator system, which includes components like the fan, water pump, A/C compressor, and power steering pump. Any new high-capacity, dual-voltage charging system will likely place significant additional mechanical strain on the existing equipment, potentially overloading the drive belt system. At minimum, it will add extra stress to the belt and any device or idler pulley located in front of it.

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If two differently sized alternators are operating on the same belt, consider placing the highest-capacity alternator as close to the tension end (balancer pulley) of the belt as possible. This may require swapping the function of the alternator positions. This way, less additional load runs through the bearings of intermediary accessory devices.

From another perspective, if only one alternator is used, it would be prudent to install the LEAST powerful alternator that would do the job to minimize the belt load and reliability impact of the other bearings in the drive system.

1) SINGLE VS DUAL ALTERNATORS

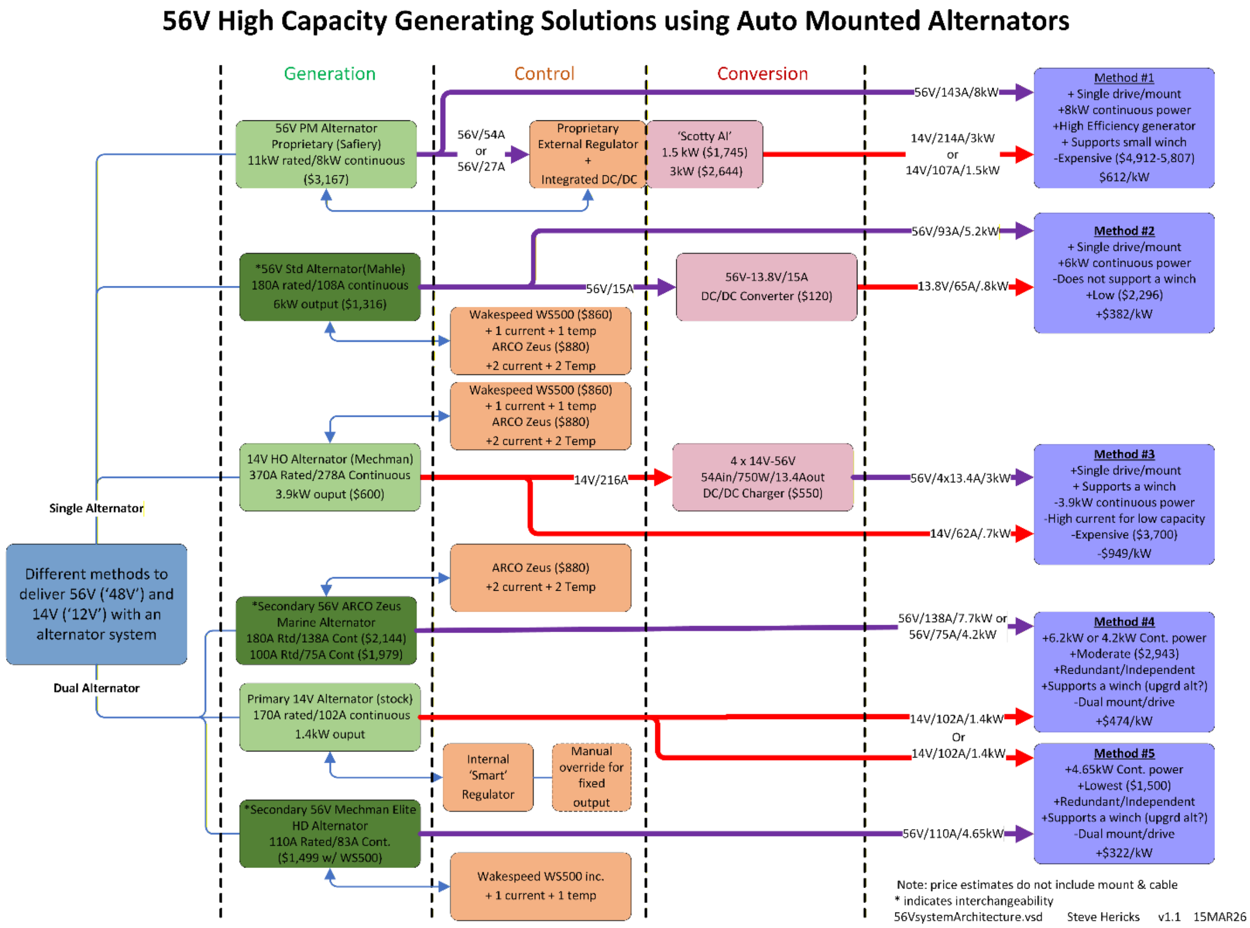

Figure 2: Optional Configurations

All vehicles will need '12V' generation for operation. How to implement a '48V' system for the habitat that still sports enough '12V' power becomes the key issue. While this may seem to require a two-generator solution, and that is probably the best solution, that is not necessarily required.

2) Single Alternator Configurations

   a. Option 1: Upgrade the existing 14V alternator to the highest possible capacity and use the additional 14V power to supply a '48V' system with DC/DC chargers;

➢ The problem is that the energy capacity of the native ´12V´ system alternator is low. Current stock alternators (for trucks) are typically rated at 150A to 200A with a continuous capacity (60% derated) of 90A to 120A (1,260W_e to 1,480W_e). Assuming a vehicle demand of 40A/560W_e (sufficient for engine operation, lights, heat/cool and convenience equipment), this leaves 50A/700W_e to

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80A/1120W_e of residual capacity available for the DC/DC charger, which is FAR lower than the design goal of 4-5kW_e.

- Enhanced aftermarket ´high capacity´ alternators, such as Mechman (premium alternator), can more than double stock capacity and provide higher continuous duty capacity. Assuming the largest, a 14V/370A-rated capacity with a 277A (3.9kW_e@75%) continuous capacity and assuming the same 40A vehicle demand, 237A is potentially available for operation of several DC/DC chargers. 237A x 14V x 95% = 3.15kW_e available. This could meet ¾ of the desired 4kW_e minimum need and is not insignificant.
- A system of 4-750W_e '12V'-'48V' DC/DC chargers (3kW_e) could be arranged in parallel and wired so they can be manually enabled individually for habitat charging based on driving time and battery debt. Hopefully, normal demand could suffice with just 2 or 3 operating in most cases.
- Large DC/DC boost chargers are expensive. These units retail for $550, so 4 would add $2,200. The cost and complexity of wiring is not insignificant. Each needs breakers at both batteries as well as individual cables between batteries.
- Charging at low idle should be absolutely prevented due to the low cooling capacity of the alternator at low RPM. Use of a 1200RPM 'high idle' (an option on many trucks) switch should be mandatory for any operation of charging at non-traveling engine speeds. Even then, charging at high idle should be operated at well less than maximum capacity.
- Delivering (40A for the vehicle and 228A for the habitat) 268A continuously at a low voltage is a very demanding cabling system. ANY weakness in connectors, lugs or bolted terminals will heat rapidly. 200A continuously is a practical ceiling, but possible. Recommended circuiting would be to minimize the length of heavy cable from the alternator to single-digit feet, terminating in a power distribution block, which immediately branches to smaller supply cables for each DC/DC charger. For example, a cable run of 30ft (both negative and positive) for 57A, requires a 2AWG cable for EACH DC/DC charger.
- Mounting space for all of this equipment is significant. DC/DC chargers need to be located in a cool, well-ventilated space, which negates under-hood and almost requires a ventilated bay in the camper. Placing the chargers in the camper presumes 4 separate cable runs of cable, each with a high-current connector.
- If the vehicle already mounts an electric winch, a higher capacity alternator should already be part of the winch installation. If it is installed, the capacity to supply one or two DC/DC chargers it is already ´paid for´ as part of the winching capability. If it has not been added, it becomes a ´two-fer´ providing capacity for both habitat support and winching. This does not meet the design goal but is about half.
- Placing a high demand on the ONLY alternator capable of operating the vehicle will likely cause thermal fatigue/shorter lifespan and could lead to earlier failure of the alternator, resulting in immobility. Lowering the reliability of the vehicle becomes more likely with higher current and longer charging duration.
- No alternators natively have thermal protection because their constant output is required for vehicle operation. Use of a thermal 'unloader' to cut off optional loads on elevated alternator temperature seems necessary.
- DC/DC chargers are rated by output power, which results in higher input power due to inefficiency. The specified Sterling Power Products devices are rated at 750W@94% efficiency. At a near max battery voltage (where max power draw occurs) of 58V the output of 750W_e will produce 750W_e/58V = 12.9A output. With a 94% efficiency (typical), this requires 750W_e/.95 = 798W input, which is (798W_e/14V=) 57A. If 4 of these were operating simultaneously, they would draw (57A x 4=) 228A, which is an extraordinarily high current and barely within the assumed capacity.

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b. Option 2: Replace the ´12V´ alternator with a ´48V´ alternator. Use a ´48V´ to 13.8V (actual) buck converter (~60A capacity) to support vehicle operation and starter battery charging.

➢ The '12V' system consists of an engine, required accessories, convenience accessories, and the '12V' starter battery. The operation might draw 30A minimally and 50A maximally. Using a 13.8V/60A converter seems appropriate. This is ONLY a converter (much cheaper than a charger) that outputs a fixed voltage (13.8V), not a purpose-made, DC/DC charger with a microcontroller-managed variable output voltage charging profile. This has the same operating characteristics as a fixed voltage ´12V´alternator.

➢ The '48V' alternator has a much higher rated capacity (4-6kW$_e$) simply due to 4x the voltage.

➢ This solution has the additional benefit of avoiding the inability or expense of the engine to mount two alternators.

➢ A shortcoming; '14V' energy is limited to the capacity of the DC/DC converter (around 60A) plus what may be surged from the starting batteries. This likely cannot support even a small electric winch. This weakness can be overcome by the addition of multiple, parallel DC/DC converters that are only powered on for winching. The cost and additional redundancy of this solution MAY be seen as a desirable enhancement. Having 3-4 13.8V buck converters with only one normally operating would provide redundancy and likely be low-cost/high-reliability.

➢ Finding a ´48V´alternator that has the same frame as a proprietary automobile, enabling the alternator to ´drop-in´ to standard mounts, is less likely as there is a smaller family of '48V' alternator mount types available. Mechman seems to have the widest variety.

c. Option 3: Replace the existing '12V' alternator with a proprietary permanent magnet alternator-DC/DC charger system.

➢ An Australian company called Safiery is producing a proprietary power system based on this system architecture. They have developed a permanent magnet, ´belt motor generator´ (BMG). Coupled with a combined DC/DC converter – CANbus controller (called ´SCOTTY´) to provide up to 11kW$_e$ of '48V' DC power while simultaneously bucking 1.5 or 3kW$_e$ to '12V' or '24V' for vehicle operation. That can be a ´whole solution´ for RV use.

➢ The Safiery system is quite expensive but would likely be highly effective in supporting a dual voltage system.

3) Dual Alternator Configurations

In general, the implementation of both a '12V' and '48V' alternator on a vehicle is fundamentally different than operating an OEM-designed ´dual alternator´ system. The OEM system uses both alternators, operating at the same voltage, delivering energy into a common electrical system. Only one alternator operates continuously, and the secondary is switched on only when the primary cannot maintain the target voltage due to the load.

Creating a dual-voltage system, by starting with an OEM dual alternator system, may be advantageous because the mechanical drive system is in place. The mount and belt drive for the '48V' alternator, which uses 4-6x more mechanical power, may need to be more robust and would benefit if the second alternator were on a separate drive belt. At this point, assume a second drive/mounting bracket is available. Although this may not be true for every truck brand/model, it is for the Ford 6.7l diesel or 7.3l gas engines on the F550. At least one '48V' alternator (Mechman) has an appropriate case. An adapter for the Ford bracket is needed if using a marine alternator.

In an OEM system, both alternators supply electricity to the native vehicle system at 12.4-15.5V. The control of both alternators is by internal regulators through the vehicle ECU/BCU. Since the ECU is 'aware' of the second alternator, removing it from the vehicle's electrical system will result in an OBD charging fault. To swap a 14V alternator for a 56V one, the vehicle will need to be taken to a dealer who can programmatically 'uninstall' the second alternator function to prevent the fault.

In a system with a 56V alternator, it will be electrically connected and dedicated to the habitat system and have no connection to the vehicle's electrical system. An alternator MUST never be disconnected from the battery it serves, meaning several things:

- The alternator regulator must never charge to a high enough SOC that can cause a single cell to reach an over-voltage condition that may cause the BMS to disconnect. Doing so causes a 'battery dump', resulting in a voltage spike that will almost certainly damage the regulator or alternator diodes, probably both. The maximum charging voltage should be set for ~90-95% SOC or no more than 56.6V, well below the maximum charging voltage of 58.4V. This specifically means that the alternator can NEVER 'fully charge' the battery (and it doesn't really matter).
- If the 56V alternator (on the vehicle) connects to the camper with a cable including a high current connector and other control lines (for power to the regulator, voltage sense, battery current shunt, battery temperature sensor) there must be a shut-off switch to cut power to the regulator before any cables are disconnected. This disconnect must also only be done with the engine off.
- The one interconnection allowed between the '12V and '48V' systems is a '48V' to '12V' DC/DC charger to allow use of the camper battery to charge or 'jump start' the vehicle starter battery. In accordance with the disconnecting admonition above, this will require a breaker or fuse near both batteries and a high amperage plug connector and 'ignition' signal wire connectors in between. A manual switch on the 'ignition' lead to disable charging under most conditions will be desirable to keep the charger turned off unless needed. If it is necessary to disconnect the camper and vehicle, the DC/DC charger's breaker at both batteries must be shut off before the connectors are separated.

The basic power and primary equipment costs are located on the architecture graphic at the head of this section. The economics of the different solutions vary quite a bit. Taking a look at the pro's and con's of each method is warranted'

<u>Method 1 – Single PM 56V alternator with proprietary control – DC/DC converter</u>. Probably the sexiest implementation. With a high-efficiency, high-capacity PM generator, it is likely very capable of producing as much power as needed with little likelihood of overheating. I'm not sure if there is a temperature sensor in the generator because with CAN bus communications with the external controller, there isn't a separate sensor cable but I think it's likely that there is a temp sensor for both the winding and the on-board converter electronics. There are two options for the capacity and voltage of the external DC-DC converter. '12V' and '24V' depending on the native voltage of the vehicle system and, 1.5kW$_e$ and 3kW$_e$ depending on the power requirements. 1.5kW$_e$ is as large as most 14V alternators can provide and far more than vehicle operation alone needs. 3kW$_e$ is large enough to support a winch. There will also be one or two '12V' lead-acid starting batteries to provide for short peak loads.

- The highest power and most efficient system.
- This is the only PM alternator solution and speaks strongly of the desirability of developing a 'mild hybrid' generator for RV use.
- For vehicles that do not have the capacity to mount two alternators, this seems the most powerful and simple.
- It would definitely violate warranty terms by eliminating the OEM alternator.
- It is expensive
- It supports a winch

<u>Method 2 - Single high-capacity 56V alternator w/ advanced external regulator & 13.8V DC/DC converter.</u> This is likely the least mechanically involved installation and, therefore, possibly the cheapest.

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A single, highly loaded alternator still presents a single point of failure being more likely to lead to failure and immobility. The '48V-13.8V DC/DC converter to support vehicle operation is a simple 'dumb' device with no communications but it doesn't need it. This is simply a 'converter' not a charger. A charger being operated by a microcontroller and capable of sensing current and adjusting voltage to suit battery charging modes. 13.8VDC is a common power supply option for powering automotive equipment and is correct for providing vehicle operating power and lead acid battery charging. If reliability is a concern, adding a parallel backup converter is an inexpensive option. The vehicle will operate just as if equipped with a 'fixed voltage' alternator.

- The assembled equivalent to the above PM solution with less integration and overall power.
- Unknown if the Mahle alternator is wire-wound or hairpin but heating calculations show that this power level needs to be hairpin if operating continuously at high outputs. Two other manufacturers of 56V hairpin solutions are listed as substitutes.
- Removing the OEM alternator would almost certainly violate warranty terms.
- One smallish DC/DC converter could not operate a winch but several more in parallel could.
- Simple DC/DC converters are relatively inexpensive.
- The whole system is relatively inexpensive.
- Using any of the 3 listed sources for 56V alternators should provide a suitable alternator case mounting stye.

Method 3: Single high-capacity 14V alternator with advanced external regulator and multiple 14-56V DC/DC battery chargers. This is relatively complex and expensive. Operating such a large bank of DC-DC chargers will need load-shedding type control to respond to elevated alternator temps because electronic loads don't respond correctly to reduced excitation. Progressive load shedding of all chargers is advisable but likely not supported by any OTS regulator. The extremely high currents expected to be produced by a 14V alternator are a cabling challenge. The chargers will need to be outside of the engine bay, likely some distance from the alternator so cable runs of large cable will be long. Connectors on high-current cables are necessary. Factory alternator cabling will need to be replaced with large cable, power distribution blocks and overcurrent protection for all chargers.

- High cost
- High current
- Challenging cabling
- Challenging load shedding
- Below minimum capacity (14V/40A/560W_e operating + 14V/228A/3.1kW_e auxiliary)
- Supports a winch
- Possibly/probably violates warranty.

Methods 4 & 5 are similar, with the factory 14V alternator powering the vehicle systems and a second 56V alternator with an advanced external regulator supplying the habitat. The two options vary only in the choice and size of the 56V alternator. This is relatively low-cost and high-reliability. The automotive power system remains intact and is the only solution that would likely not violate the warranty. Choosing the higher capacity alternator may not result in proportionally higher continuous capacity, and only provide some peak capacity. Contravening notes on the graphic, theoretically, hairpin alternator capacity hits a heat dissipation limit ceiling at ~4-5kW_e. This is far from certain and depending on vehicle and environmental conditions, some additional continuous capacity could be realized with a larger alternator.

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- Requires dual alternator mounting and drive system
- Relatively low cost and high reliability
- OEM alternator system unaffected.
- Redundancy
- Simpler cabling compared to other solutions
- Load shedding not required (no electronic loads involved).
- More overall power and heat dissipation with 2 alternators

IX. CONCLUSIONS

1) Alternator mounting method
   a. Dual alternators are more desirable because they afford;
      - More total output power
      - Double the heat dissipation
      - Increased reliability by maintaining the automotive system (and warranty) intact.
      - Complete separation of the power systems by voltage and purpose.
   b. Mounts and drive systems are available both from OEM and aftermarket for the F550 7.3l gas engine.
   c. Vehicle savings result from omitting the dual 14V alternator option on the vehicle purchase because the second alternator is not useful and an aftermarket alternator kit with bracket and drive system is available (Mechman).
2) Alternator
   a. Conventional (wire wound) alternators cannot produce the required continuous power (4-5kW_e) because their low efficiency (~50%) produces unsustainable waste heat (>1.3kW_t).
   b. Only hairpin or PM alternators are efficient enough to produce 4-5kW_e continuously.
   c. Only one PM alternator (Safiery) is of adequate design and capacity, but is (IMHO) very expensive relative to more economical and adequate hairpin designs. It may be a good choice if only one alternator could be mounted, but it is not the best option when dual alternators are available/desirable.
   d. Prices for marine alternators are significantly higher than similar performing automotive hairpin designs. I see no advantage to ‘marine’ designations over automotive.
   e. Mechman appears to be the only manufacturer able to supply a ‘48V’ automotive alternator with a Ford T-case mount used on the Ford 7.3l gas engine.
   f. Mechman sells a complete kit with alternator, dual mount and Wakespeed regulator for a 7.3l gas engine in an F550 for $1,700. I plan to purchase the mount and alternator but purchase an ARCO Zeus regulator separately.
3) Regulator
   a. An external regulator is required and is best purchased separately from the alternator.
   b. Balmar MC-620 regulator is unique with ‘12V’ excitation even for ‘48V’ alternators so it only operates with Balmar alternators, which are very expensive. Additionally, as the low-price regulator leader, it lacks current sensing without buying into a much larger battery management system.
   c. One current sensor (for the alternator) is required. Dual current sensing (alternator and battery) is desired.

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d. One temperature sensor (for the alternator) is required. Dual temperature sensing (alternator and battery), is beneficial and desired.
e. External controls for load shedding is desired and should be required if using a DC/DC charger.
f. While the Wakespeed has 1 current and 1 temperature sensor, it has no external controls.
g. Since the cost of the ARCO Zeus and Wakespeed regulators are essentially the same price, but ARCO has more features, better Bluetooth connectivity (remote antenna) and app. It seems the best choice.

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Terms

- ‘Power’ is a <u>rate</u> of energy transfer in units of Watts (W) or kilo-Watts (kW). Since this analysis addresses energy transfer in terms of both electrical energy and heat energy, I use ‘kW_e’ for electrical power and ‘kW_t’ for thermal (heat) power. This notation is uncommon for the general public but is normal in the power generation industry.
- ‘Energy’ is a <u>quantity</u> of energy in units of Watt-hours (Wh) or kilo-Watt-hours (kWh). Since I only address energy in electrical terms, I don’t append the ‘$_e$’ to kWh. It is implied that all energy measures are electrical.
- A ‘12V’ automotive power system is called ‘12V’ because a 6S (6 cells in series) lead-acid battery has a voltage at 50% SOC of 12V (precisely, 12.04V).
- Power system; When I put the voltage in single quotes (’12V’), I am referring to the entire power system that includes generation, storage, and powered equipment, all operating within a standard voltage range. ‘12V’ systems run from 10.5V of a fully discharged lead-acid battery to 15.5V of a ‘smart’ alternator in ‘regenerative braking’ mode. Voltage ranges for ‘24V’ and ‘48V’ systems do not experience regenerative braking; therefore have a voltage range from 21V/42V to 28.8V/57.6V. The voltage range of these systems is based on lead-acid battery characteristics that will change slightly when the system uses LFP batteries.
- ‘SOC’ is State of Charge, meaning the amount of energy contained in a battery relative to its actual (not theoretical) capacity. If a battery has a theoretical capacity of 1280Wh, but that capacity has degraded to 1000Wh, and at the moment, it contains 900Wh. It has a SOC of 900Wh/1000Wh = 90%.
- ‘SOH’ is State of Health, meaning the actual capacity of a battery relative to its theoretical capacity. For instance, if a battery has a specified (in ‘new’ condition) capacity of 1280Wh, but during charging and discharging, it is shown to have an actual capacity of 1000Wh, its SOH is 1000Wh/1280Wh = 78%.
- ‘Amp-hours’ is an antiquated measure of battery capacity. This measure is only useful when comparing batteries of the same nominal voltage. Batteries only have the same nominal voltage if they are of the same chemistry. For this reason, Watt-hours are the only effective measure when comparing systems using different battery types since they have different nominal voltages.

Batteries

- Batteries used in any system proposed herein will be assumed to use Lithium Iron Phosphate (LFP) chemistry cells.
- If a ‘12V’ lead-acid battery is rated at 100Ah, it has a storage capacity of 12V x 100Ah = 1200Wh. For a lead-acid battery, the amp-hour rating is defined (by lead-acid battery standards) to be over a 20-hour discharge (referred to as a ‘C/20’ rate). Therefore, this 100Ah capacity is ONLY going to be realized if it discharges at equal or LESS than a 5A rate (100Ah/20 hours = 5A) over 20 hours. If it discharges faster, say in 4 hours (a ‘C/4’ rate), the battery discharge curve (created by the manufacturer) will show that it only typically has 65Ah of capacity at a C/4 discharge rate. This means that lead-acid batteries have a rate-based capacity and lose energy internally if rapidly discharged. LFP batteries exhibit little of this rate-based derating.

Alternator

- A ‘12V’ system ‘fixed voltage’ alternator operates between 14.2V to 13.8V but, on average, around 14V, which is why I refer to a 14V alternator whenever I am talking about it as a component of a ‘12V’ system. The automotive alternator is (only) designed to support vehicle operation and charge its associated lead-acid starter battery.

- Charging an LFP house bank, if the charging source is a vehicle alternator, requires some form of voltage and current control that can only be provided by;
  - An external ‘charging’ regulator on a second alternator.
  - A battery-to-battery charger.
  - Constructing an intentionally resistive cabling system to increase the network resistance to be high enough that excessive amperages may be kept below absolute maximums has been done. The issue is that running a fixed resistance system is greatly affected by the voltage differential between the charger and the battery. Typically, it will only operate satisfactorily if the battery is above 50% SOC. When below 50% SOC, the charge rate becomes excessive.
  - A ‘Battery Isolation Manager’ is a device sold by Battleborn Batteries to force intermittent charging. It is a voltage-sensitive timer relay that connects the alternator to the batteries for 15 minutes during which the alternator may (almost certainly will) operate above its continuous capacity, heating up significantly, then disconnects for 20 minutes. The intent is to allow charging at an unknown, unregulated rate, then disconnect to provide an opportunity for the alternator to cool down. This has several potentially severe problems: 1) Every vehicle and battery bank will act differently. 2) Even the same vehicle and battery bank will act differently at different states of charge. 3) Neither the charging rate nor the temperature is monitored, and there is no way to know if either operates within reasonable limits. It is nearly certain that the alternator will overheat to some degree. 4) Disconnecting a very large load that may be as big as several hundred amps (the device is rated at 225A), will create a ‘load dump’ that causes a large voltage spike in the alternator on every disconnection. This voltage spike can damage the regulator or diodes and can travel beyond the alternator and through the entire vehicle's electrical system to potentially damage vehicle electronics. 5) A ‘smart’ alternator-equipped vehicle, needs alternator voltage to be boosted to charge effectively. The BIM does not boost voltage. 6) While the device is rated at 225A, it has no overcurrent protection or mechanism to limit excessive current. It relies on the inability of the alternator to deliver more than 225A (which is likely a good bet).
- Although the peak charging voltage of 6S lead-acid is 14.4V and 4S LFP is 14.6V, alternator systems are not designed to be stage-controlled battery chargers and therefore are not capable of ‘fully’ charging connected batteries. This is a very good thing. In the case of LFP, there is a major risk of the BMS disconnecting and causing a ‘battery dump’ if only one cell reaches maximum voltage. If the LFP battery were the only battery attached to the alternator and it were to remove itself from the charging circuit under load, the resulting collapse of the magnetic field in the loaded alternator will produce a large voltage spike. Without the damping provided by the battery, the spike will course through the entire connected electrical system. A ‘battery dump’ will likely damage to the alternator’s diodes or regulator and possibly other unprotected electronics in the electrical network.
- When designing an alternator system to charge RV batteries, any alternator that provides electricity to the vehicle and auxiliary batteries simultaneously is incapable of performing as a ‘staged’ charger, even if the regulator is designed for it. With the vehicle loads drawing energy in parallel with the battery charging, the extra loads cause voltage and current fluctuations that prevent the charger from sensing the battery condition. Alternator charging should be considered only a ‘bulk’ stage charger, capable of rapidly reaching 80-90% SOC where the solar system completes the final 10% charging after the engine is off.
- Marine alternators can be purchased in ‘isolated ground’ versions. These alternators have both positive and negative terminal studs, and neither is electrically connected to the case. This is intended to support non-(hull) grounded marine systems but is also very useful in automotive applications where output current measurement is desired. In most cases, current shunts are negative side devices, making measurement of grounded case alternators impossible.

Voltage

- A system's standard voltage is based on the nominal battery voltage (the voltage at 50% SOC) of its connected battery. In the past, this standard applied to systems made from multiple, series-connected, '12V' lead-acid batteries, which is where the '12V', '24V', '36V', and '48V' terminology originated.
- '12V' system standards generally also include LFP batteries with a slightly higher nominal voltage (12.8V vs 12V). The commonly referenced '12V' system standard continues to be used, even with LFP batteries, because, in general, the detailed specifics of individual systems do not alter the fundamental principles. In the case of a lead-acid system, voltages range from 10.5V of a fully discharged battery to 14.4V maximum charging voltage. Because there is substantial overlap with LFP having a full voltage range of 10.0V of a fully discharged battery, to 14.6V maximum charging voltage, there is more in common than exceptions.
- The ACTUAL nominal voltage of an LFP cell is NOT 3.2V as commonly stated. It is actually 3.26V. This means the <u>real</u> nominal voltage of a 4S battery is not 12.8V, but 13.04V. I believe the 12.8V nominal was adopted by the industry to be able to continue to refer to it as a '12V' system, rather than a '13V' system, to make it seem more compatible. Keeping to a single decimal point seems likely also desirable. If 3.26V were to be rounded to 3.3V, a 4S battery would now be a 13.2V battery, which may be even 'scarier'. The falsification also benefits battery manufacturers who would have to make a battery rated in Ah, using slightly more active material if the '13V' actual nominal voltage were used. While this differentiation is technically accurate, all data in the market is based upon the use of the 3.2V standard, so it should be seen as a 'distinction without a difference', other than when using 'State of Charge (SOC) charts.
- Voltages referencing batteries are 'nominal' voltages. A nominal voltage is the voltage of the specific battery chemistry at 50% SOC. The nominal voltage of a traditional 6S (6 cells in series) lead-acid battery is 12V. 4S LFP batteries have a nominal voltage of 12.8V. Similarly, 16S LFP batteries are 51.2V.
- The rate of charge is based on the voltage differential between the charging source and the battery. If charging either lead-acid or LFP from an internally regulated 'smart' alternator, a battery-to-battery charger MUST be used to boost the typically low alternator output voltage (~12.4V) to a higher voltage suitable for battery charging (13.8V or greater).
- A '24V' power system has its origin as a vehicle system using 2 series-connected '12V' lead acid batteries. This was common on heavy trucks and military vehicles. As such, this system operates on exactly twice the voltage of a '12V' system. '36V' systems are 3x '12V' system voltages and '48V' systems are 4x.
- Because Maximus does not have a '24V' vehicle operating system, I use a second 28V alternator solely as a house battery (a 7S Lithium-Nickel-Manganese-Oxide (NMO) battery at 25.5V nominal) charging system, and may tend to refer to it generically as a '24V' system or a 28V alternator.
- '48V' power systems were never an automotive standard but existed, having been adopted as a further multiplication of 4 series-connected lead acid batteries that allows higher power transmission for stationary applications. '48V' systems are now used in a wide variety of applications. To reduce system complexity, they are used with 'Mild hybrid' equipment in passenger vehicles, and on large farm tractors to power secondary electrical systems in towed implements. It is also a broadly used standard for residential solar system backup power. As such, the '48V' lead-acid standard is almost non-existent and almost exclusively refers to 16S LFP batteries at 51.2V nominal, 40V minimum, and 58.4V maximum.
- Voltages referencing alternator systems use peak output voltages needed to power the equipment and also charge the connected battery system. An automotive alternator has an

approximate peak voltage of 14V. This is the operating voltage of the entire attached electrical system when the alternator is operating.

- The output of traditional (not 'Smart') alternators is designed to operate vehicle systems and charge a lead-acid battery, but the internal regulator has a negative temperature coefficient so as not to overcharge the lead-acid starting battery when the under-hood environment heats up. Designers assume the alternator is in the same engine compartment as the battery AND the battery will be experiencing similar under-hood temperatures. In cool ambient temperatures, the alternator may produce 14.2V but that voltage drops to around 13.8V over the 10-20 minutes it takes for the engine to warm up. This is specifically intended to prevent over-charging a 12V lead-acid battery that is undergoing a temperature rise due to engine heat exposure.
- Similarly, a 56V alternator peak voltage is the legacy carryover of a 24S lead-acid battery system. The peak voltage of a 16S LFP battery is 58.4V. In environments where external alternator regulators are present, alternator output is both adjustable and programmable. When connected only to a battery bank, the alternator/regulator combination BECOMES a multistage battery charger. External regulators can normally be adjusted to voltages higher than 58V. For our purposes, 56V will be the reference used for consistency, although actual thresholds will be different.

Appendix B: Possible Equipment

Equipment Available to Implement Potential Systems				
Device Type	Description	Rated Capacity	Interface	Price
Alternator/Generator				
Permanent Magnet Generator	Ford 'Mild Hybrid' motor/generator	56V/250A/14kW$_e$	Proprietary (unavailable?)	$268.32 eBay
Permanent Magnet Generator	Safiery BMG J180 mount + Scotty	56V/196A/11kW$_e$ >85% efficiency. 5kW$_e$@idle, 8kW$_e$@cruise.	Proprietary 'Scotty': 1.5KW$_e$ or 3kW$_e$ 14V/28V DC-DC	BMG: $3,166.83 3kW$_e$: 2,644.37 1.5kW$_e$: $1,746
Conventional Alternator	Mahle (Slovakian)	56V/100A/5.6kW$_e$ 3.4kW$_e$ cont.	External 48V Regulator (Wakespeed/ARCO)	$876.67 + duties
HD Alternator	Mechman Mechman.com	56V/110A/6.2kW$_e$ 4.65kW$_e$ continuous	External 48V Regulator (Wakespeed/ARCO)	$1,499 w/WS500, $1,699 w/WS500 & dual bracket
HD Alternator	Leece-Neville pad mount	56V/85A/4.8kW$_e$ 3.6kW$_e$ continuous	External 48V Regulator (Wakespeed/ARCO)	$1000 eBay.com
Conventional Alternator	Mahle (Slovakian) J180 mount	56V/180A/10.1kW$_e$ 7.6kW$_e$ continuous	External 48V Regulator (Wakespeed/ARCO)	$1,316.47 + duties
HD Alternator	Mechman	14V/370A/5.2kW$_e$ 3.9kW$_e$ continuous	External 14V Regulator (Balmar/Wakespeed/ARCO)	
Marine Hairpin Alternator	ARCO A800-48V Isolated ground	56V/180A/10.1kW$_e$ 7.6kW$_e$ continuous 55A@2500RPM 111A@4000RPM	Arco Zeus External 48V Regulator	$2,143.90 NVNmarine.com
Marine Conventional Alternator	Balmar 96-48-60-K6-IG	56V/60A/3.4kW$_e$ 2.5kW$_e$ continuous	External 48V Regulator: MC-620 (12V excitation)	$3,016.48
Marine Conventional Alternator	Balmar 96-48-100-K8-IG	56V/100A/5.6kW$_e$ 4.2kW$_e$ continuous	External 48V Regulator: MC-620 (12V excitation)	$3,016.48
External Regulator				
Marine Advanced Regulator	Balmar MC-620-H	12/24/48V w/ 12V ONLY excitation (?)	Alt temp sensor optional. No current sense	$470.37
Marine Advanced Regulator	Wakespeed WS500	12/24/48V w/ respective excitation	Allows: 1-temp sense, 1-current sense	$649,+$80 short harness, +$170 long harness, + $30 temp
Marine Advanced Regulator	ARCO Zeus	12/24/48V w/ respective excitation	Allows: 2-temp sense, 2-current sense, 3-I/O, Bluetooth App	$796 std , $880 w/long harness + 2 temp
Power Conversion				
DC-DC converter	Unbranded eBay.com	48V-13.8V		50A: $116 60A: $120 80A: $200
DC/DC Charger	Sterling Power Products	14V-56V DC/DC charger (bidirectional)	BB124865 (750W$_e$)	$550

These notes are intended to be separate but because they are related to the same device, understanding one may facilitate understanding of another. While these statements are usually presented as absolutes, which will be conceptually consistent, there are environmental or situational factors that can add variation or create exceptions.

1) Alternator efficiency is a measure of input mechanical power (in kW) to output electrical power (in kW_e). The difference between input mechanical power and output electrical power is waste heat (in kW_t - thermal). Heat is the enemy of alternators and becomes a key problem for high-power alternators. The design of an alternator has a significant impact on its efficiency and, thereby, heat generation. Alternator efficiency is low for traditional regulated designs and is broadly variable. The efficiency of all regulated designs decreases with load and RPM.
   - ´Standard´ alternators use a wire-wound stator coil that have typical efficiency at cruise of ~50%. For example; a $1kW_e$ 'standard' alternator operating at 50% efficiency requires ($1kW_e/.5=$) 2kW mechanical input power and produces $1kW_t$ of waste heat (equal parts electricity and waste heat).
   - Premium alternators may be called 'marine' or 'high-output,' but they all have a critical feature called a ´hairpin´ stator winding with larger, square-section wire that is packed more densely and capable of operating at 75% efficiency under normal speed and loads. A 25% increase in efficiency may not seem dramatic, but it is. For example, a $1kW_e$ premium alternator requires ($1kW_e/.75=$) 1.33kW of mechanical input power and produces $0.33kW_t$ of heat. Comparatively, this is 2/3rds of the input energy with one third the waste (of a 50% efficient design) to deliver the same electrical energy.
   - Permanent Magnet (PM) alternators are sold as unregulated. For our purposes, unregulated types are not useful. High, constant magnetic flux from the permanent magnet rotor coupled with a high-density rotor, generates with high (>90%) efficiency. PM alternators generate voltage proportional to RPM so to deliver a stable output at varying engine RPM, a regulated type is used in proprietary applications where it processes the generated electricity through an on-board DC/DC converter (also >90% efficient) to electronically convert output to a uniform voltage. The microcontroller operating the DC/DC converter can vary the output voltage based on control parameters. Overall efficiency for a PM alternator is typically >85%.
2) The waste heat needs to be dissipated by the fan in the alternator, which does not move much air at idle. High generation needs at least medium (~4,000 alternator RPM) speed to keep the alternator cool. Because of the high heat generated at high load, less efficient alternators cannot sustain their 'rated' capacity for long, about 15 minutes, before overheating (exceeding 120C/148F). In practice, most alternators never operate at their rated capacity and only produce high outputs for a minute or two to recover battery starting debt.
3) An alternator's 'rated' capacity is based on a factory bench test specified in SAE J56/ISO 8854. These tests use 23C/75F cooling air, dumping electricity into a fixed resistor, occurring over the time it takes to run the alternator from 0RPM to 6000RPM and back down (less than a minute). There is never a consideration of temperature. The alternator has thermal mass, which will take time to heat up, and the test is over before it ever reaches an equilibrium temperature. That is not true for its continuous output when supporting vehicle operation.
4) Alternators typically only produce high power for a few minutes to recover starting debt, so in their intended role, they don't need nor are they capable of extended high energy generation at or near their rated capacity.
5) Some form of current control must be used to prevent overloading the alternator when charging lithium batteries.

- A lead-acid battery has an 'internal resistance' of around 50-100mΩ. It's charge rate is based on the difference between the battery voltage and alternator voltage, usually not more than a couple of volts. As the battery 'charges', the battery voltage rises, reducing the differential, slowing current. It is, relatively speaking, difficult to cause high current to flow into a lead-acid battery.
- A J56 load bank resistor produces no voltage of its own. Current is produced relative to the full voltage drop applied by the alternator. The resistor converts all electricity to heat and does not 'charge up', so there is no change in resistance to current flow. This allows the resistor to absorb the full capacity the alternator is capable of producing, which is why a resistor is used for the test and not a lead-acid battery. This is also one of the reasons that the rated capacity of an alternator impossible produce in a vehicle.
- An LFP battery has an internal resistance of less than 2mΩ (about $1/50^{th}$ of a lead-acid battery), which means the battery will produce 50X the current with the same voltage differential. The resistance of batteries placed in parallel drops with each battery connected, increasing the current. LFP batteries have such low resistance that they can accept current FAR more readily than even a load bank resistor. They behave as a 'short circuit' whose resistance is characterized mostly by the cabling in the network rather than the battery itself. Such a low-resistance network will accept current limited only by the source's ability to deliver. If the source does not have the ability to deliver that current continuously, it will overheat and burn out. This also ignores the battery's maximum safe charge rate.
- Because battery charging is a long-duration activity, an assumption of the alternator's actual continuous capacity is made by applying a derating factor to the alternator's rated capacity. Assume standard wire-wound alternators are derated to 60% and premium designs using a hairpin stator to 75%.

6) Directly charging lithium from an alternator provides no control of current. Current flow is a result of Ohm's law where $(V_{alternator}-V_{battery})/R_{battery} = I$. Lithium batteries have an internal resistance of significantly less than 2mΩ for a single, 12.8V/100Ah battery, and will be less than 1mΩ for two or more batteries in parallel.
7) Charging current examples;
    - If charging a single 100Ah LFP battery alone using $V_{battery}$ @ 50% SOC = 12.8V and $V_{alternator}$ of 14.0V, the current would be 14.0V-12.8V/.002Ω = 600A.
    - Since some cabling must be connected, assume 2-10ft cables of 2AWG battery cable (with a resistance of .129Ω/1000ft), the added resistance of .0026Ω. Just adding battery cables doubles the network resistance from .002Ω to .0046Ω. Charging current is 14.0V ($V_{alternator}$) – 12.8V ($V_{battery}$)/.0046Ω = 261A.The current is still well over the alternator's continuous capacity and more than twice the 1/C rate of the battery. If the alternator can provide this without overloading, this current exceeds the battery's 1C maximum charge.
    - If you double the cable length to 40ft., 14V-12.8V/.0072Ω = 167A, current still exceeds 1/C (100A) allowable and almost definitely exceeds the alternator's continuous if not rated capacity.
    - It only gets worse of the battery SOC is lower and if there are more batteries in parallel. Looking at a worse-case example of two fully discharged batteries in parallel with 20ft of 2AWG positive and negative cable. Charging current is 14.0V ($V_{alternator}$) – 10V ($V_{battery@0\%SOC}$)/(.001$\Omega_{2battery}$+.0052$\Omega_{40'cable}$) = 645A. Again, 3x the battery max charge rate and obviously way over the alternator capacity.
8) It is highly likely that charging could occur when the battery is near or fully discharged. $V_{battery}$ of 10V (0% SOC) charging current could be (14V-10V)/.005mΩ = 800A. This is 8x the battery's 1C maximum charge and likely 6x the alternators. If this battery were to be able to be charged at this rate, it would

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be complete in 8 minutes. Since the battery voltage will climb, and charging will slow, unrestricted charging would take ~4x that time.

9) If there were 2 -50% SOC batteries in parallel, the charging current would be 240A total with 120A for each. This almost certainly would exceed almost any alternator's capacity. The larger the bank and the lower the SOC, the greater the likelihood of alternator failure due to overload/overheat.
10) No allowance is made for the resistance of the cable network between the batteries and alternator, which is relevant but unknown and highly variable.
11) TBL: Potentially injurious uncontrolled charging will result in widely varying and potentially huge currents at low battery SOC's. Alternators do not have thermal protection devices as do most motors and generators.
12) A ´typical´ alternator has several negative characteristics that become magnified at higher power, so simply getting a 56V version of a 14V alternator needs consideration. The performance graph below is for a 14V/170A Ford alternator, but it is typical of wire-wound alternators.

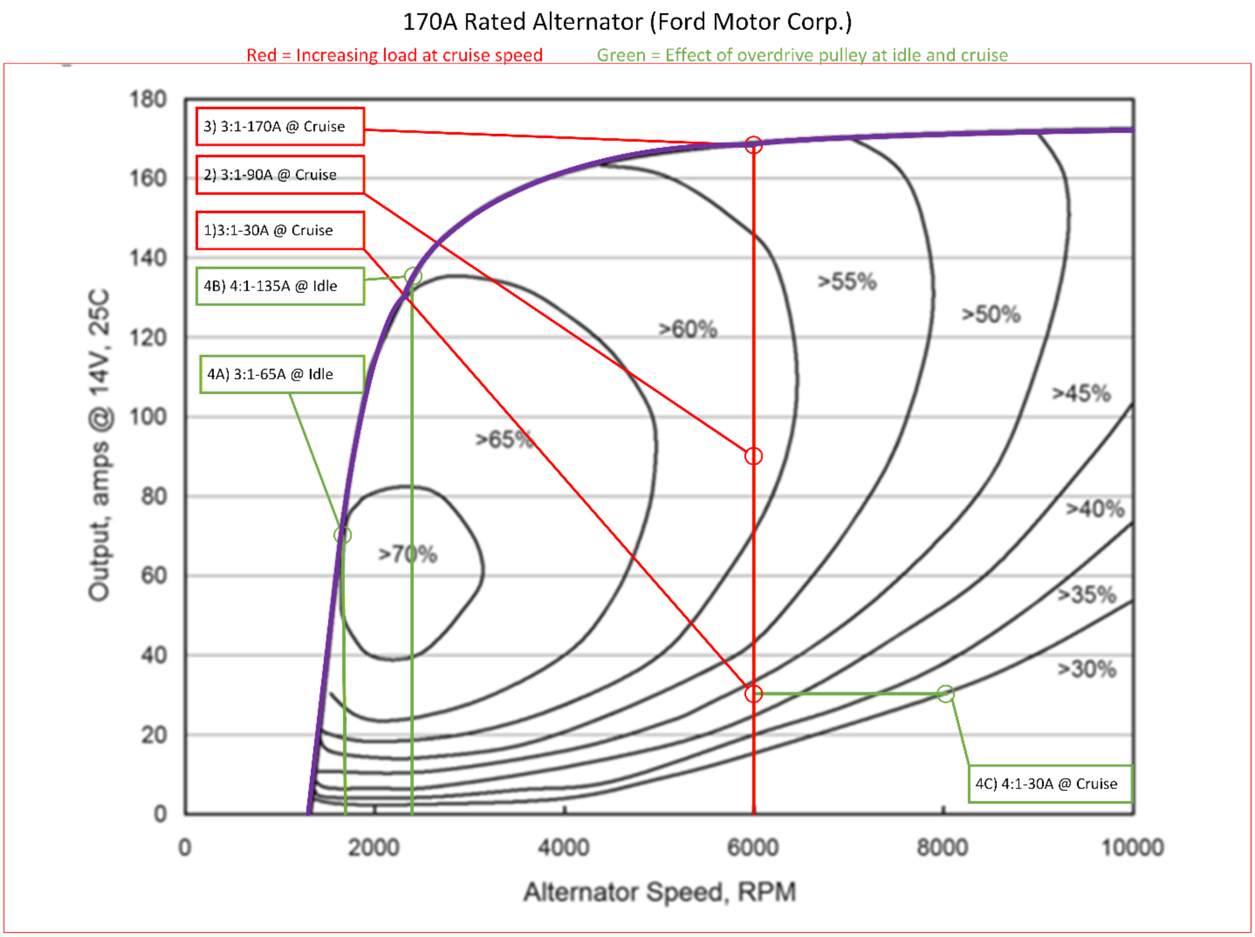

Figure 2: Ford 170A Alternator – Effects of Load and RPM

13) Effect of efficiency: A typical automotive alternator has relatively poor efficiency. It ranges from a maximum of 75% at low speed and load to 30% at high speed and low load. Efficiency matters a lot in alternators because producing high power at low efficiency generates a lot of heat that, at higher loads, cannot be dissipated.

➢ Scenario 1 – Cruise with minimal load: If a 170A-rated alternator is putting out 30A/420W$_e$(18% load) of electrical power at cruising speed (6,000 alternator RPM/2,000RPM engine RPM - typical 3:1 for a truck engine), by the chart above, it is operating at 38% efficiency. It will require an input mechanical power of $420W_e/.44$ = 954W(1.3HP). The difference of (.95kW – $420W_e$) $530W_t$ is the heat being created inside the alternator.

- Scenario 2 – Cruise with auxiliary load: If a 170A-rated alternator has a demand of 90A/$1.26kW_e$ (40A operating + 50A DC/DC charger = 53% load assumed acceptable to be continuous), it's operating efficiency rises to 62%, operating at the same engine speed. The input power now needs to be (90A x 14V/ .62) = 2kW (2.8HP). Of this 2kW input, $1.26kW_e$ is electricity, and $740W_t$ is heat generated inside the alternator. With no change in engine RPM, cooling airflow has not increased. Compared to scenario 1, 3x the minimum power is being produced with 1.4x the heat. The great benefit is that efficiency has significantly increased, allowing available cooling airflow to keep the alternator temperature below maximum (120C/248F).
- Scenario 3 – Cruise with maximum load: If a 170A - rated alternator has a demand of 170A/$2.38kW_e$ (100% load is theoretically possible when directly connected to n LFP battery), its operating efficiency is at 58%. The input power now needs to be (170A x 14V/ .58) or 4.1kW (5.5HP). Of this 4.1kW input, $2.38kW_e$ is output as electricity (2.5x minimum cruise) and $1.72kW_t$ is heat generated (3.2x minimum cruise) inside the alternator. With the drastic increase in heat with no increase in cooling, it should be obvious that the alternator will quickly overheat operating at rated capacity.
- Scenario 4: - Changing to an 'overdrive pulley' to increase potential idle output (green annotations); If a 170A alternator were fitted with a 33% 'overdrive' (smaller diameter) pulley, potential idle output increases, but heat generation becomes detrimental at cruising speed. Changing the standard drive of 3:1 to 4:1;
  - The original alternator RPM at idle with 600 engine RPM and 1,800 alternator RPM with potential output of 65A@.7 efficiency produces $910W_e$ electrical/$390W_t$ heat.
  - The 'improved' system increases alternator RPM at idle to 2400RPM with potential output of 135A@.64 efficiency. The potential output is $1.89kW_e$ electrical/$1.1kW_t$ heat. The maximum output at idle doubles, and the heat generation triples with little increase in cooling air circulation and no increase in engine compartment air exchange (operating at idle, by definition, is not moving).
  - The original alternator RPM at cruise speed is 2,000 engine RPM and 6,000 alternator RPM with an actual demand of ~30A to operate the engine, 14V/30A @ .44 produces $420W_e$ electrical and $530W_t$ of heat.
  - The 'improved' alternator RPM at cruise speed is 8,000 alternator RPM. With an actual demand of ~30A to operate the engine, 14V/30A @ .3 producing $420W_e$ electrical and $980W_t$ of heat. The amount of heat nearly doubles because the higher RPMs depress the alternator's efficiency.

14) Alternator mechanisms with either wire-wound or hairpin stators are virtually identical (size, weight, and cooling capacity) in their ability to dissipate heat. The output voltage of 14V and 56V alternators changes the output power by a factor of 3-4x. If the heat generation of the alternator also scales at 3-4x, the alternator is at major risk of overheating.
15) The low efficiency of an alternator is a ´feature´ of both the need to regulate the voltage over a broad range of RPM (resulting in poor magnetic coupling) and low hardware cost. Manufacturers are not motivated to implement more efficient designs for the mass market, which does not demand them. Higher-performing alternators definitely cost more. Manufacturers' motivation is to pursue the lowest-cost, adequately performing device, in particular, because it generates for a short time, producing low voltage and low power.

16) Take note that the higher fuel efficiency demands of CAFE standards resulted in OEM's changing to 'smart' alternators that couple reduced generation with energy recovery using a slightly larger conventional alternator rather than increasing alternator efficiency. Higher efficiency alternator

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designs are achieved by creating better magnetic coupling between the magnetic rotor and windings in the stator in two different ways;

- Improve the stator windings: Typical coils using 2 or 3 parallel wires are replaced by large rectangular (rather than round) wires, resulting in more dense conductor packing. This is called a ´hairpin stator´. This design increases the efficiency of the alternator by ~20%. Most 56V designs corporate hairpin stators.
- Improve the rotor magnets: Voltage regulation at progressively higher speeds requires reducing the strength of the rotor electromagnet, thereby reducing magnetic coupling and comparable efficiency. By using permanent magnets in the rotor instead of an electromagnet, the magnetic field strength is constant (and magnetic coupling is high), but voltage can no longer be regulated at the stator output. Output voltage varies with engine RPM. To make it useful, the variable voltage output is processed by a DC/DC buck converter mounted on the back of the alternator that receives the generated variable voltage and electronically converts it to a fixed voltage. PM alternators are capable of 93% generation efficiency and DC/DC converters operate around d 95% conversion efficiency, yielding ~88% overall efficiency. Due to vastly improved efficiency, these designs have a much lower heat generation and can achieve 10-12kW$_e$ outputs. At the time of this writing, only Safiery produces a system using this design that could readily be incorporated into an RV.

17) Alternator Sizing based on Heat Dissipation Capacity

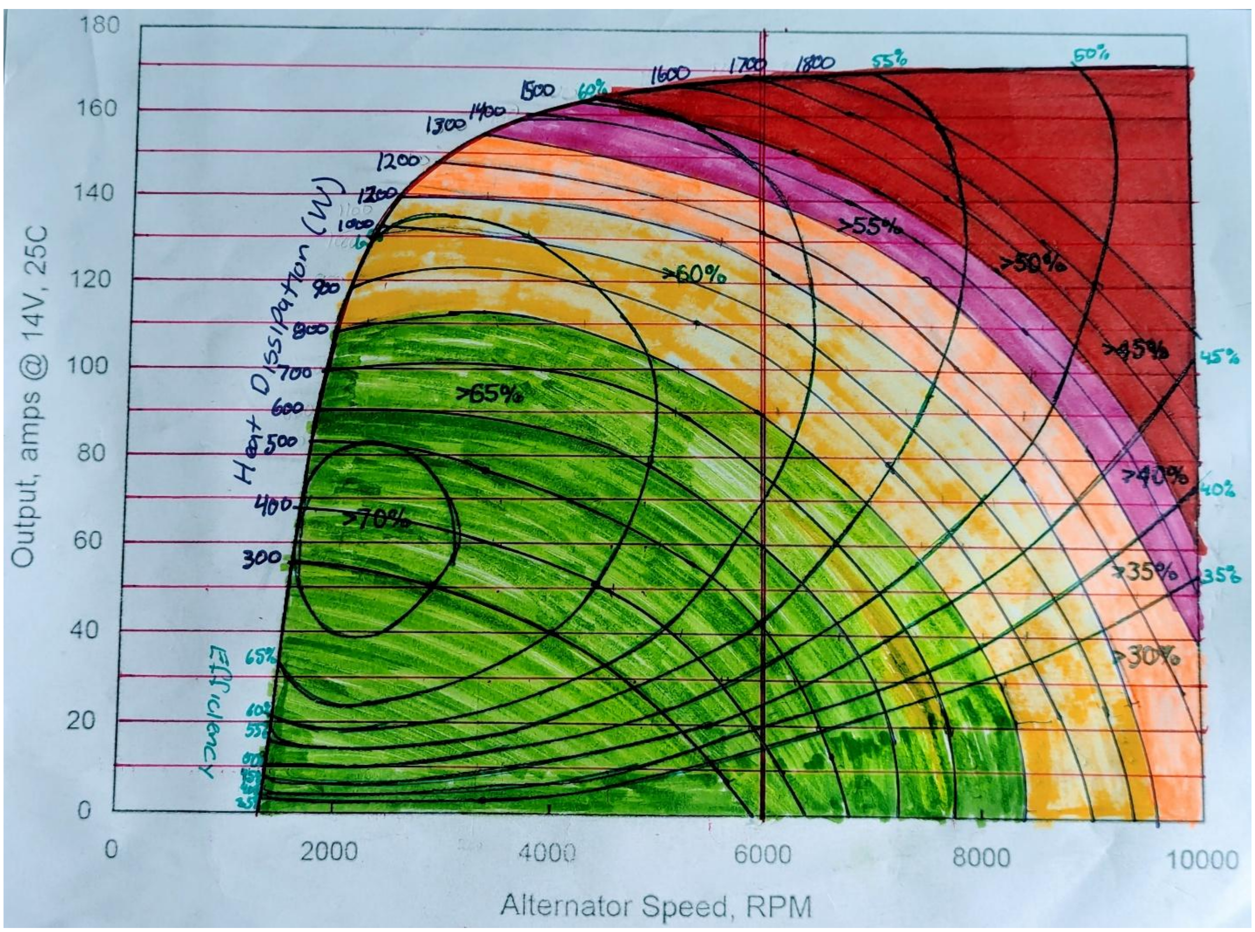

Figure 1: 170A Ford Alternator Heat Generation

The chart above is based on an original Ford 170A-rated SAE J56 alternator output test (black curve) with efficiency zones (green lines). I have calculated and added a heat generation overlay (purple curves with colored zones), indicating the waste heat the alternator would produce based on the output (14V@ indicated amperage) and efficiency. I make the following observations;

- It is well known that 'rated output' is effectively a short-term (single-digit minutes) capacity and cannot be sustained for long periods due to overheating. This chart is an attempt to evaluate the relative quantity of heat being generated at all output levels to approximate the maximum, continuously sustainable output.
- This chart is specifically for heat generation. What we really want to know is how hot the alternator will get based on the combined heat generation and fan-forced cooling. When the rate of heat generation exceeds the rate of cooling, alternator temperature increases. The magnitude of the cooling airflow is not known and varies widely with engine RPM and load. It cannot be easily quantified, but we can understand the effect on the shape of the curve. If this chart were to be modified to include engine heat, engine compartment airflow, under-hood temps, and alternator fan air movement over the RPM rage, the effects of cooling, should 'bend the curve' down at low RPM (indicating less capacity at low RPM) AND also 'bend the curve down' at high RPM due to high engine temperature and plateauing engine compartment airflow, both increasing cooling air temperature AND lowering alternator fan airflow due to blade stall. The following would noted;
- Dissipation at idle (no vehicle movement) would be low because radial vane blowers are poor air movers at low RPM and engine temperature would be low enough that engine fans would not engage to improve engine bay airflow. Most heat generated would remain in the alternator and dramatically increase the temperature.
  - Dissipation at cruise speed (45-60MPH) would presumably place the alternator's blower at optimum airflow. Air movement by the motion of the vehicle would also be beneficial. Dissipation will be high.
  - Dissipation at high vehicle speed/engine RPM will drop significantly. The radial blade fan will enter the stall region, (the fan blades are moving so fast, they 'slip' through the air rather than grab and accelerate it), and airflow will decrease from the peak, likely by 50% or more. Airflow through the engine compartment will have peaked at mid speeds and be obstructed by the much larger slipstream of the vehicle. High engine temperatures will increase under-hood temperatures. High alternator speed will place the alternator at the lowest operating efficiency.

18) The current 'rule of thumb' for estimating continuous duty capacity is 60% of the rated capacity of wire-wound stators and 75% for hairpin stators.

19) Because almost all automotive alternators are of a similar design, similar wire insulation, size, mass and operate in the same environment, they will also;
    - Experience the same temperature rise from the same amount of waste heat.
    - With all mechanical things being similar, once an alternator's output is large enough to produce 1.3kW_e of waste heat, the continuous capacity has been reached. If it begins operating at a capacity above the 'continuous', the temperature will steadily increase, resulting in damage to the diodes and wire insulation.
    - Larger-rated capacity (wire wound stator) alternators will contain larger stator wire (a small mass increase) and higher capacity diodes but these will not increase the continuous capacity because nothing in its construction increases the heat dissipation capacity.
    - The type of stator winding creates two different categories of output based on efficiency at the same waste heat level. Hairpin alternators can produce a higher output at the same amount of waste heat. 1.3 kWh of waste heat in a 50% efficient, wire-wound alternator limits its output to 1.3 kW_e. Meanwhile, 1.3 kW_t of waste heat in a 75% efficient, hairpin alternator limits its output to 4 kW_e.

20) This comes down to an essential physical truth, that ALL alternators reach their continuous output limit at the same waste heat generation, which will vary based on environmental conditions (because cooler environmental conditions provide cooler air that increases heat dissipation), but is likely around $1.3kW_t$-$1.5kW_t$. Some evidence;

- Safiery claims a continuous output of $8kW_e$ with a total efficiency of 88%. This yields total mechanical input of $8kW_e/.88$ = 9.1kW with $1.1kW_t$ of waste heat.
- To achieve the goal of $5kW_e$+ electrical production with less than $1.3kW_t$ of heat generation, that would require a base efficiency of $5kW_e$ /6.3kW = 80%. This is easily achievable by PM alternators (no doubt why this design is used for generation in excess of $10kW_e$) but is just over the upper limit of hairpin alternators. What is the production limit for a hairpin alternator? With 75% efficiency, limited to $1.3kW_t$ waste heat = $3.9kW_e$ electrical output maximum.
- Applying the same logic to conventional alternators with 50% efficiency, when limited to $1.3kW_t$ waste heat = $1.3kW_e$ is the maximum continuous electrical output (14V/93A).
- This theory posits that because alternators are all the same size, mass and have the same cooling means, REGARDLESS of their rated capacity, their maximum <u>continuous</u> output is limited by their ability to dissipate THE SAME maximum amount of heat. The only way to increase capacity, is to increase heat dissipation. The two ways to do that are 1) increase efficiency or 2) improve cooling.

Extrapolating on the above logic, installing a significantly higher capacity hairpin alternator than ~$3.9kW_e$/56V = 70A continuous or 70A/.75 = 93A rated capacity may only provide increased peak production, but would not result in higher continuous capacity.

- Possible ways to improve heat dissipation;
  - Remove the diode bridge from the rear case of the alternator and relocate it to a location with better/cooler airflow. Doing so removes the rectification heat load from the alternator and provides better airflow through the back of the alternator. This was done with Maximus' 28V/220A alternator and it resulted in ~20% (estimated) greater production.
  - Cool the alternator with fan forced air from outside the engine compartment (~60F cooler air). Air induction into the alternator is from the front and rear. Since the belt drive is on the front, direct duct connection will be difficult. In some mounting locations, accessing the rear may also be difficult. Since most alternators are on the top half of the engine, improving any natural source of airflow is likely difficult. If the alternator were on the bottom of the engine, airflow would seem most easily achievable.

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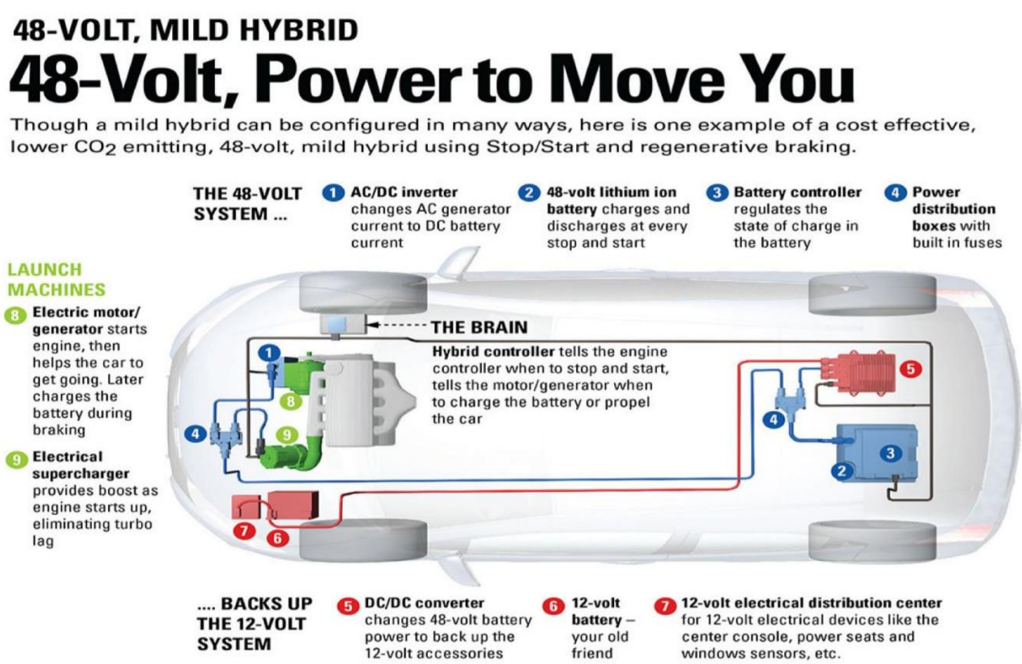
Appendix D: 'Mild Hybrid' 48V PM Alternators

A new generation '48V' motor-generator-battery system is being used in EURO6-compliant automobiles (only in Europe). EURO6´s fuel mileage mandates have resulted in the creation of a new category of hybrid vehicles commonly called ´mild hybrids´. These vehicles use less powerful, less complicated, lower-voltage ('48V') hybrid electric motor/generator systems than those used in 'full' hybrids.

Typical hybrids use proprietary, HIGHLY integrated motor-generator systems, usually operating at 360V and using batteries of ~5-10kWh capacity. Mild hybrids are built with a far less complex system that replaces the belt-driven '12V'(~1kW_e) alternator with a '48V'/10-15kW_e permanent magnet motor-generator. The 'mild hybrid' belt-driven mechanics significantly simplify the design while also significantly lowering the system's power and benefits. Generating '48V' and using a '48V'/3-5kW_e battery, the motor-generator (still proprietary) is an attractive possibility for use as an RV generator.

- OEM motor-generator units from EURO6 mild hybrids are available on the used parts market, inexpensively (~$300). They are manufactured by Ford, Jeep, BMW, Audi, VW and Mercedes, etc.
- Since these units are permanent magnet designs, they require substantial electronics on the back of the unit that contain both a 'Brushless DC' (BLDC) motor control for when the unit is used in ´motor mode´ and a DC/DC converter that takes the unregulated generator output and converts it to a voltage suitable for charging the '48V' battery. This is all controlled through CAN bus by proprietary controllers.
- IMHO, getting a generator to operate in anything other than the intended vehicle may be difficult and expensive. It will specifically require an electronic microcontroller capable of communicating with the DC/DC converter to control output voltage.
- Some mild hybrid motor-generators have adapted to high heat generation by being fully water-cooled, some use only water-cooled electronics, and some are completely air-cooled. Water-cooled systems are 'low temperature' and separate from the engine coolant system.
- The Ford units are most attractive for modification as they are air-cooled and rated at '48V'/250A.
- IMHO, the high efficiency and power available in these units are a tremendous asset, making them highly desirable for RV applications.



Simple Alternator Thermal Safety w/ Manual Override Switch

Connecting optional loads to a vehicle electrical system, such as charging auxiliary batteries, places a heavy load on the alternator. At times, the added load may cause overheating, leading to failure. This simple thermal switch provides a means of sensing overheating and temporarily disconnecting optional loads when it occurs. Overheating is likely when alternator demand exceeds capacity relative to driving and environmental conditions:

- Low airflow from low engine or vehicle speed.
- High engine bay temperatures when hauling heavy loads, climbing hills, or at high ambient temperatures.
- High vehicle electrical demand when operating headlights, heating or A/C system, wipers, seat heaters, etc.
- Optional loads exceeding the alternator's continuous reserve capacity.

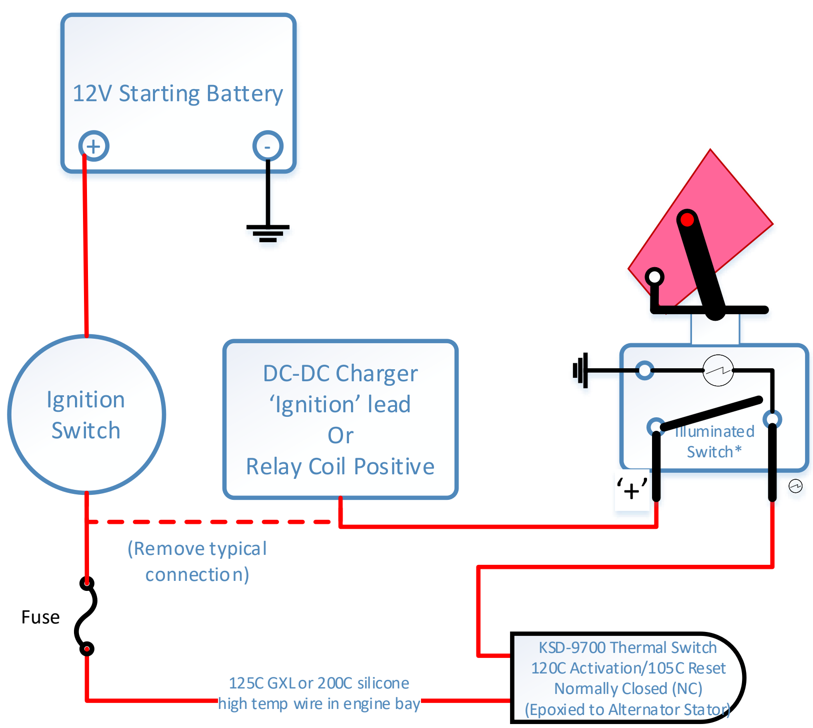
Epoxying a KSD-9700 thermal switch to the center of the alternator case senses the winding temperature. Connecting the leads in series with the circuit provides 'permission to charge' to the DC/DC converter ignition lead or split charge relay any time the alternator temperature is safe. When the alternator temperature exceeds safe limits (120C), 'permission to charge' is withheld, disconnecting charging.

The disconnect temperature is selected when purchasing the switch. The recommended activation temperature is 120C. When the alternator heats to 120C, the switch opens, disconnecting the optional load. When the reduced electrical load allows the alternator to cool by 15C/27F, the switch closes, turning the optional load back on. The optional load can safely cycle on and off to maximize charging while always preventing the alternator from overheating.

To allow manual control over optional charging, an override switch placed in series in the same circuit allows the driver to enable/disable charging. Disabling charging could be desirable when solar charging is sufficient (fuel savings), demanding driving conditions are anticipated, or the ambient temperature is high. Using an illuminated switch will communicate if/when the thermal switch opens.

1) Normal Operation (override switch 'ON'): The normal switch position is recommended to be installed with the cover down being 'ON' (protected). Ignition power flows from the ignition switch, through the thermal switch and manual override switch to signal the optional device to operate. The indicator light visible through the cover and is illuminated any time the alternator is less than 120C/248F indicating auxiliary power is 'available'.
2) Manual Override (override switch 'OFF'): When the manual override switch is up/'OFF', ignition power is cut to the optional device, turning it OFF. If the indicator light is illuminated, power is passing through the thermal switch indicating the alternator is below 120C/248F showing charging is available.
3) Thermal Override (switch not illuminated): If the alternator temperature exceeds 120C/224F, (regardless of override switch position), the thermal switch opens, interrupting the ignition signal which prevents operation of the optional device. When alternator temperature reduces below ~105C, the thermal override will close, the indicator light will illuminate and if the manual override is down/'ON', optional equipment will resume.

NOTE:
- At no time will alternator power be disrupted to vehicle systems. This ONLY reduces the load on the alternator by shutting of the optional equipment.
- 'Load shedding' of large relay connected loads will cause a voltage spike on disconnection but the starting battery and avalanche diodes in the alternator will damp reasonable disturbances.
- If controlling a split charge relay, ALL operating DC equipment in the camper will experience voltage fluctuation between alternator voltage (~14V) and camper battery voltage. This is already a normal experience when starting and stopping the vehicle.



Manual Override Switch
(Covered toggle switch)
Mounted near driver.
Cover rotated 180 to be 'OFF' when up/ 'ON' when down.
Illuminated when alternator charging is available regardless of switch position.

* Connecting the illuminated switch in this manner is considered 'backwards' (power and signal terminals wiring reversed) because the indicator light is illuminated when power is available at the manual disconnect, not just when the manual switch is in the 'on' position. This is intentional and correct. The illuminated light indicates the power is flowing to the manual switch through the thermal switch circuit, indicating that the THERMAL switch is active and does NOT indicate the position of the manual switch.

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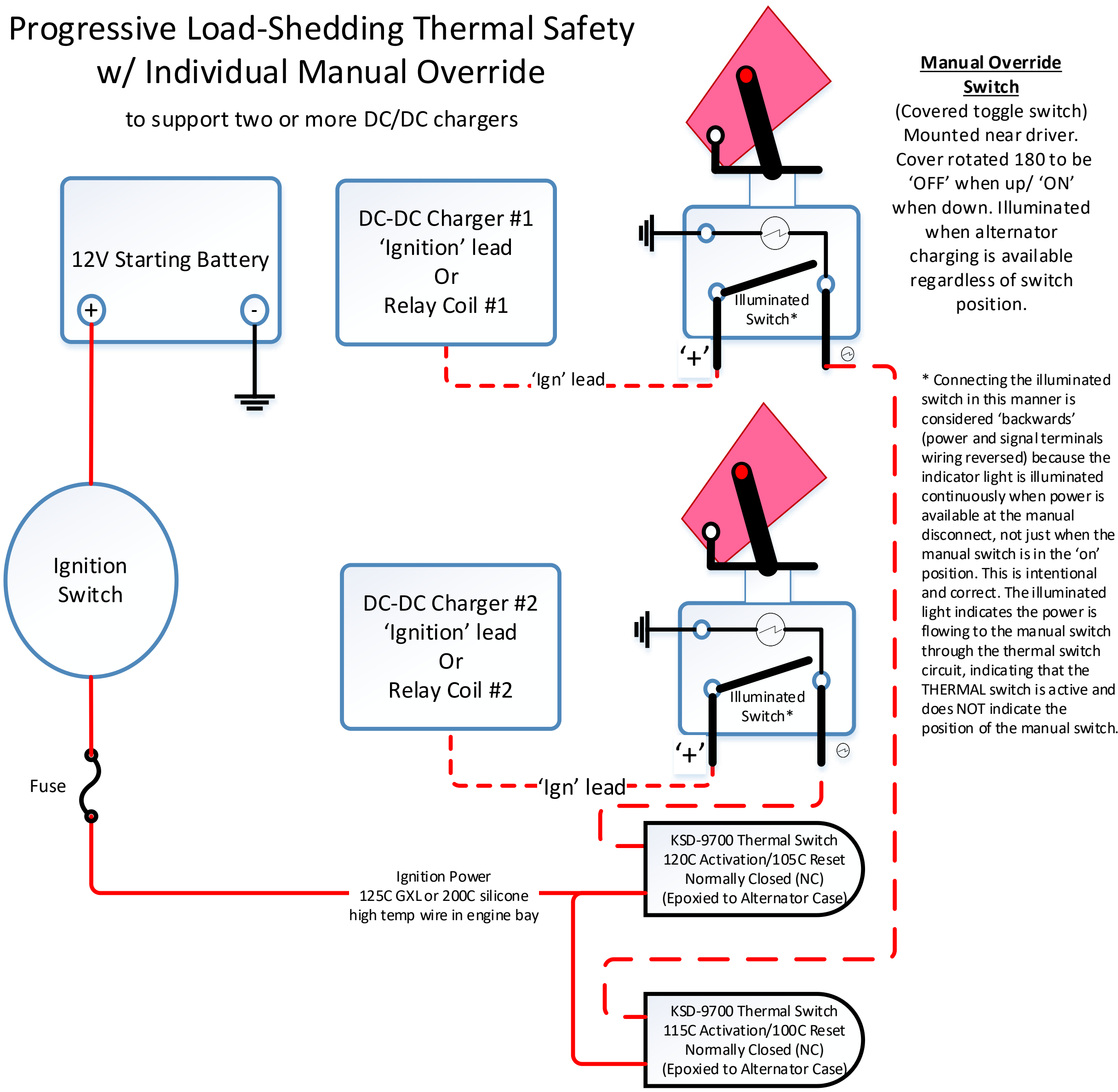
Progressive Load-Shedding Thermal Safety w/ Individual Manual Override

to support two or more DC/DC chargers

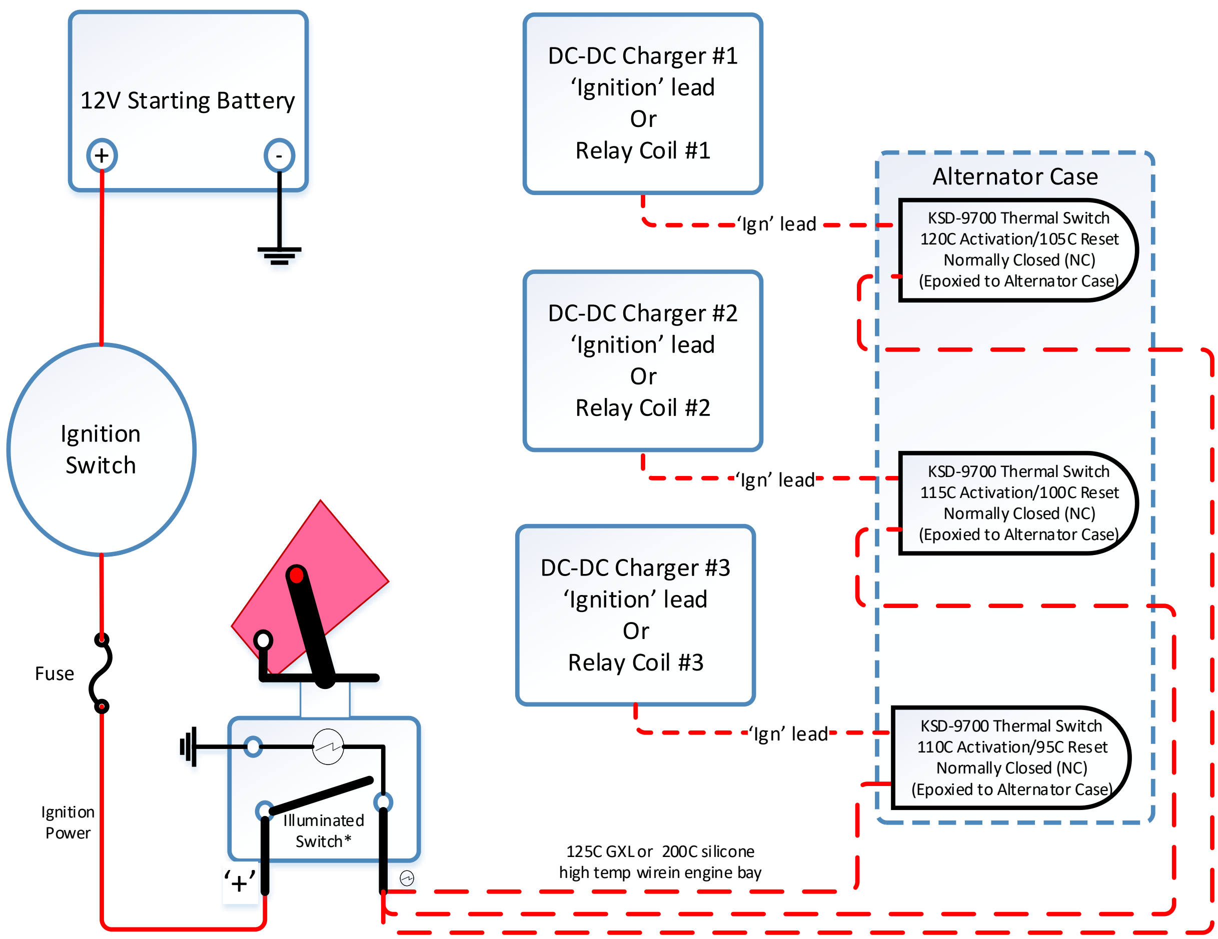


This schematic indicates how to construct a 'cascading' thermal safety circuit for 2 (or more) DC/DC chargers operating from the same alternator. Both KSD-9700 thermal switches are epoxied together on the alternator case. One switch has a lower activation temperature causing one charger to disconnect (at 115C) before the other (at 120C). This provides a progressive load shedding.

If both chargers are 'on' and the alternator reaches 115C, one will disconnect. If the temperature continues to rise, the second will disconnect. If the temperature stops rising but does not drop below 100C, the system will continue to operate with only one charger. If either or both disconnect and doing so allows the alternator to cool off significantly, they will both automatically reconnect at 15C below their activation temperature. Both also have manual disconnect switches with indicator lights. The indicator light shows the state of the thermal switch (illuminated = charging available/switch closed), not the manual switch position.

If more than 2 devices are connected, activation temperature for each added device should be 5C lower than the current lowest device so progressive load shedding will occur. The highest temperature device should be 120C. Separate manual switches for each device is not necessary but the indicator light will not be available to indicate activation of load shedding for each device.

Progressive Load-Shedding Thermal Safety For Multiple Devices w/ System Manual Override



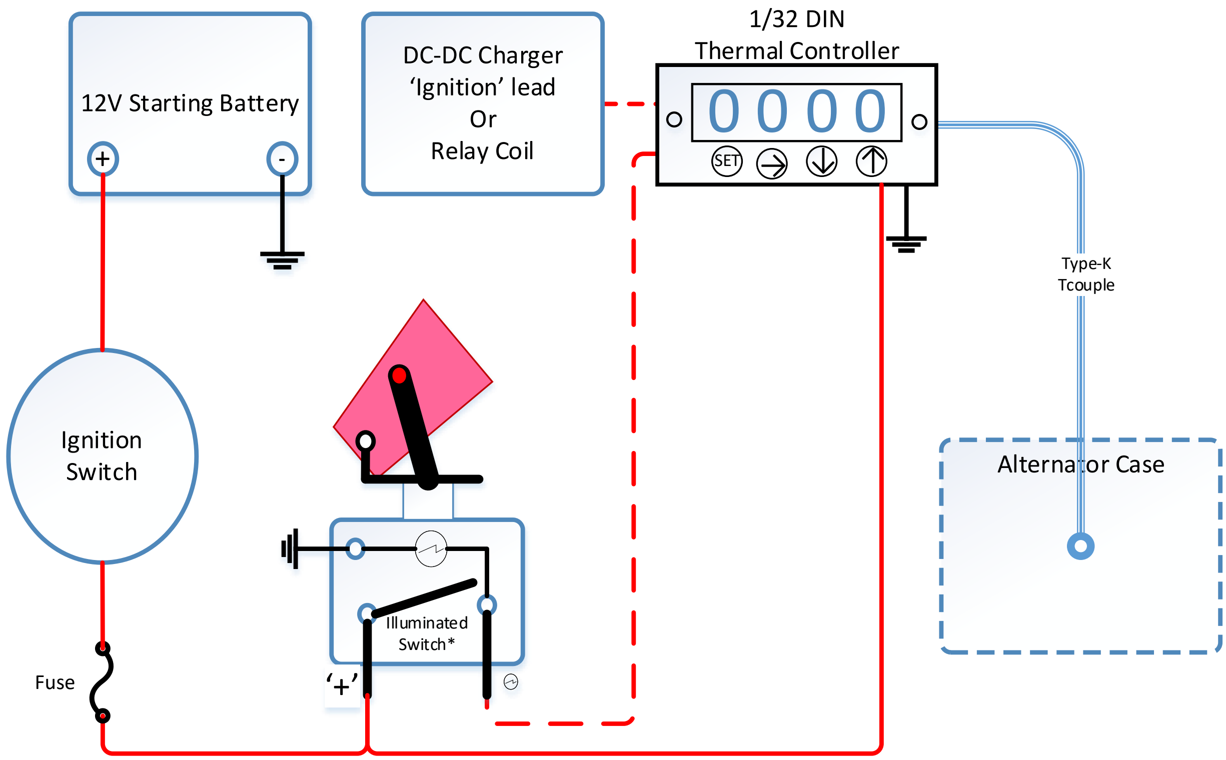
Manual Override Switch
(Covered toggle switch) Mount near driver.
Illuminated when alternator charging is available.

This schematic indicates how to construct a 'cascading' thermal safety circuit for 2 (or more) DC/DC chargers operating from the same alternator. KSD-9700 thermal switches are epoxied together on the alternator case. Each switch has a lower activation temperature causing each charger to disconnect at progressively higher temperatures. This provides a step-wise load shedding.

The manual override switch affects all devices in the system. If 'on' and the lowest thermal activation temperature is reached, the first device will disconnect and the remaining will continue to operate. If the temperature still continues to rise, the second will disconnect, then a third. At any point, if the temperature stops rising but does not drop below the reactivation temperature of the first unit that disconnected, the remaining units will continue to operate. If enough disconnect that the alternator to cools off significantly, they will reconnect in turn. The indicator light shows the state of the override switch, illuminated = charging available. Nothing indicates the state of the thermal switches.

If more devices are connected, activation temperature for each added device should be 5C lower than the current lowest device so progressive load shedding will occur. The highest temperature device should be 120C.

Appendix E: Alternator Thermal Safety/Automatic Load Shedding



Manual Override Switch
(Covered toggle switch) Mount near driver.
Illuminated when alternator charging is available.

This schematic indicates how to construct a thermal safety circuit for a DC/DC charger operating from an alternator. It is based on a 1/32DIN (12mm x 24mm), 12VDC thermal controller (~$50 for generic) sensing the alternator case temperature with a Type-K thermocouple. Larger sizes can display the current temperature and set point simultaneously. The controller has an internal 2A relay in series between the ignition switch and the ignition terminal of the DC/DC charger. Reaching the activation temperature (120C) opens the internal relay, disabling the DC/DC charger.

The manual override switch provides ignition power through the relay. Turning the override switch 'off' allows the controller to display temperature but disables the DC/DC charger. Both the activation temperature and reset temperature are programmable.

If more than one charger is used, use KSD-9700 at 5C progressively lower temperatures than the thermal controller for cascading load shedding. Only one thermal controller is needed to display alternator temperature. Maximum disconnect should be 120C.