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IN PURSUIT OF THE *Perfect* CHARGING SYSTEM

Story And Photography By
JAMES AND JENNIFER HAMILTON

Configuring a marine charging system to perform well is a difficult task. We've read about and heard from many people who have struggled with this issue.

The problem is more complex than it should be, as much of the advice from armchair experts is incorrect or fails to give the full solution. Many approaches will produce a poorly performing system or a maintenance headache. We've experienced both.

In an effort to rise above these challenges, we'll begin with a review of the conventional wisdom on marine charging systems, with an emphasis on providing important details that are often left out of such analyses. Then, we'll discuss some of the fine points that can make the difference between creating a charging system that falls short and one that is maintenance free and meets its design goals.

BATTERY BANK DESIGN

For those who don't want the noise, maintenance, and expense of a generator, a good solution is having a large house battery bank coupled with a substantial charging system, plus an inverter if 110-volt power is needed. (We will not cover the selection of inverters here; instead, we'll focus on battery banks and charging systems.)

Many different house battery bank designs have been proposed over the years, ranging from large single banks to multiple banks. We use a single house bank that is separate from the starting bank. The two banks must be separate to avoid the risk of a discharged house bank draining the starting batteries to the point that the main engine cannot be started. Why have a single house bank rather than two or more? Battery life is inversely related to discharge depth. Batteries that are discharged only slightly during each cycle can last for many years and thousands of charging cycles. Batteries that are pulled down close to full discharge may not live to 50 discharge cycles. Understanding this, it makes sense to put all non-starting batteries in a single bank and to minimize the discharge depth of the overall bank.

The type of batteries used for the house bank affects the overall charging system design parameters. Just about every battery type that exists has strong proponents who offer good support for their opinions. Battery selection depends on your design goals. Our optimization criterion is a simple one: we want the cheapest source of current when considering the entire life of the battery. We don't mind adding water to a battery. For our goals, flooded lead acid golf cart batteries remain the best choice. Golf course operators with many carts in service care about the same thing we do: maximum current delivered at the lowest overall cost.

What follows is specific to flooded lead acid batteries, but the basic principles apply to all marine batteries. The main differences are in recommended discharge rate, discharge floor, charging voltage, and charging rate. If you are looking for batteries that optimize characteristics such as low servicing requirements, the ability to not leak when turned upside down, or maximum safety, you may choose a different battery type. A good starting point for research is the tutorial at batterystuff.com/tutorial_battery.html.

SIZING THE BANK

Now that we have decided to go with a single large house bank made up of flooded lead acid batteries,

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BATTERY CAPACITY

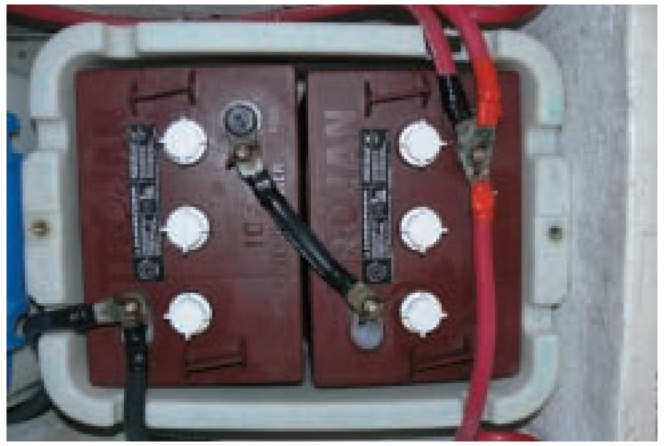
Battery capacity is measured in many different ways, including cold cranking amps, marine cranking amps, reserve capacity, and amp hours. Deep-cycle house batteries are rated in amp hours. The amp-hour rating is the sum of the number of amps that the battery can continuously deliver for 20 consecutive hours. Trojan T-105 golf cart batteries, for example, are rated as 225Ah at 6 volts.

When designing a battery bank, identical batteries of the same age or vintage are cabled together in parallel, positive post to positive post and negative post to negative post. The amp-hour capacity of the bank is the sum of the capacities of the batteries in the bank. Battery bank design is made slightly more complex with golf cart batteries, since they are 6-volt batteries and most boats use 12-volt house battery banks. The trick here is to cable pairs of 6-volt batteries together in series, with the positive post on one attached to the negative post of its pair. Each 6-volt pair forms a 12-volt composite battery that can be wired in parallel as described above. Although the pair's voltage combines, the amp-hour rating does not: two 225Ah, 6-volt batteries produce a 225Ah, 12-volt composite battery.

As an example, if we were using 225Ah golf cart batteries and wanted a 600Ah bank at 12 volts, we would need six batteries. This six-battery bank would be composed of three pairs of batteries, with each pair cabled in series. Each pair has a capacity of 225Ah at 12 volts. These three pairs, attached in parallel, form a house bank of 675Ah at 12 volts.

how do we determine what capacity is needed? To answer this question, you must inventory all power consumers on the boat. Determine how many amps each device draws and approximately how many hours that device will be on during a 24-hour period. This will produce a full day amp-hour budget. For example, our refrigerator draws a robust 7 amps, but only for 15 minutes per hour (the run time is longer in warmer climates). Its 24-hour cycle cost is 42Ah. We run many other power-hungry devices, including three laptops. Our total 24-hour budget is 360Ah.

Next, decide how many days you need to be able to last between charges. Because our power consumption is fairly high and our battery space is limited, we can go only a single day between charges. Those who are willing to use less power or are able to carry more batteries can choose a longer period. Much less than a day won't work well, since charging house batteries in the middle of the night will disturb you and others. Multiply the amps hours required per day by the number of days between charges to obtain the total amp-hour requirements between charges.



Battery bank design is made slightly more complex with golf cart batteries, since they are 6-volt batteries and most boats use 12-volt house battery banks. Here, the Trojan batteries are well secured in a battery box inside the boat's engine room, though the lid has been removed for this picture. It's important to have the battery box well ventilated for flooded lead acid batteries.

The next step is purchasing batteries. The battery capacity that will be needed is much larger than the total number of amp hours required between charges. The reasons for this are (i) discharging a flooded lead acid battery below 30–50 percent charge shortens its life and (ii) charging a flooded lead acid battery above an 80–90 percent charge is inefficient.

We have already addressed the first point: flooded lead acid batteries hate deep discharge. Regularly discharging the batteries below 30 percent will reduce the life of all batteries in the bank. We rarely go below 50 percent, and never below 30 percent. Conventional wisdom and experience dictate that discharging a battery or bank below 50 or 60 percent (that is, leaving a 40–50 percent charge) is detrimental to a battery's overall longevity. The limiting factor on the high side is that charging beyond 80–90 percent, although great for the batteries, is slow. Flooded lead acid batteries charge quickly up to about 80 percent charge. Beyond this point, because the internal resistance of a charged battery increases, the batteries charge progressively more slowly. Depending on the system, charging the bank from 40 percent up to 80 percent might take two hours, and charging that last 20 percent of the way to 100 percent might take an additional two hours or even longer.

Given that discharging below 30–50 percent is bad for the battery and that charging beyond 80–90 percent is slow, the next step is to decide the range over which the house bank will be used. Fifty to 80 percent is ideal, but 40-85 percent is also reasonable. Let's look at an example using the 40-85 percent range and a 675Ah house bank at 12 volts (see the "Battery Capacity" sidebar). Eighty-five percent of the total 675Ah bank is 573Ah; we won't depend on charging beyond this level. Forty percent of the 675Ah bank is 270Ah; we won't discharge below this mark. Subtract 270 from 573, and you have 303Ah of usable capacity.

This may seem low, given that we started with 675Ah. If greater capacity is needed, more batteries may be added to the bank, or the bank may be regularly charged above 85 percent to increase its usable capacity at the cost of increased charging time. (Shorepowered chargers used dockside are typically capable of replacing this remaining percentage, albeit slowly.) Like all things in boating, it is a compromise. Adjust your power consumption, the usable capacity range, the number of days between charges, and the space allocated to batteries, and you will eventually settle on a bank size that is suitable for your usage.

You also need a way to ensure that the discharge level doesn't fall below the minimum you select. Many inverter control systems support a discharge floor for this purpose. When set to 40 percent, for example, the inverter will automatically shut off if the bank discharges below this level. We choose not to use this feature and have instead permanently mounted a large digital voltmeter where it is visible throughout the saloon. Using this method, we can monitor charge level at a glance.

From here, three issues remain to be considered. First,

Many inverter control systems support a discharge floor to ensure that the discharge level doesn't fall below the minimum you select. We choose not to use this feature and have instead permanently mounted a large digital voltmeter where it is visible throughout the saloon. We can monitor charge level at a glance.

DIFFERENT CHOICES, DIFFERENT CHARGES

There's a distinct relationship between the charge acceptance rate of different battery chemistries (flooded, gel, and AGM) and alternator output.

Flooded batteries can accept only about 25 percent of the bank's amp-hour capacity in charge output. Thus, a 400Ah flooded battery bank should not be charged by an alternator whose output exceeds 100 amps. Conversely, gel and AGM (absorbent glass mat) batteries can accept approximately 50 and 100 percent, respectively, of their amp-hour capacity in charge rate.

Thus, a key component of charging system design is the relationship between the size of the bank and its charge source. While gels and AGMs may cost more than golf cart batteries, they charge much more quickly, which means less engine run time and wear and tear, and less engine noise for the crew. Plus, running the engine strictly for battery charging, under light load, can be detrimental to it.

Tracking the amp hours, voltage, and battery state of charge is an integral part of any battery monitoring system. The user must be able to determine when a bank has reached the critical 50 percent discharge and 80-90 percent charge states, and this is virtually impossible to determine without an amp-hour monitoring device.

Battery discharging and charging is not linear; a formula known as Peukert's equation applies. If a battery bank can deliver 100 amps for one hour, it doesn't mean it can deliver 200 amps for half an hour. Likewise, if an alternator puts out 100 amps and a battery bank has discharged 100 amps, it typically takes more than an hour of charging to replace those amp hours (often, a factor of 1.5 applies, but it depends on the type of battery and the ambient temperature).

The primary advantage of drawing a battery bank down to 50 percent charge (and recharging to 80-90 percent) is that this will allow it to deliver the greatest number of amp hours over its lifetime. Shallower discharges mean more overall charging cycles, and the number of amp hours delivered per cycle will be less. Deeper discharges provide more amp hours but fewer charging cycles over the lifetime of the battery bank.

Whatever work you undertake on your vessel's electrical system, whether you do it yourself or hire a pro, ensure that it meets all the relevant guidelines spelled out in ABYC's Chapter E-11, "AC and DC Electrical Systems."—Steve C. D'Antonio the automotive alternator/regulator combinations delivered with most boats won't efficiently charge a deep-cycle bank. Second, many alternator charging specifications are somewhat optimistic in the charge rate they advertise. Third, both the house and starting batteries must be charged without the risk of discharging both together and being unable to start the main engine.

EQUIPMENT NOTES

Following is a list of equipment brands and vendors in the Seattle area that we use. We do not imply that these are the best, nor do we gain from their mention. These are merely products or vendors we have used in the past. Our intention is to provide a reference point from which you can conduct your own research.

- Batteries: Trojan T-105s (trojan-battery.com). Other golf cart batteries are equally serviceable.
- Digital voltmeter: Blue Sea Systems DC Digital Voltmeter 8235. We can easily read the large display through our electrical panel's tinted glass doors.
- Electrical repair: Ballard Electric (www.ballardelectric.com) in Seattle has always provided us with good service and reasonable pricing. They specialize in alternators, starters, batteries, and DC motors such as those used in windlasses and power winches.
- External regulator: Balmar Max Charge 612 (balmar.net/page15-maxchargemain.html). This unit has more features than necessary, but we love the fact that it's a nearly infinitely adjustable, multistage regulator. A Charles Industries multistep alternator regulator is another good choice. Voltage regulation is not that challenging of a problem, and most brands will work equally well.
- Infrared heat gun: This is an invaluable tool that should be in every boater's tool kit. We use a RAYTEK 4XX07.
- Inverter: Heart Interface Freedom Model 30 with a Link 2000 inverter control panel (xantrex.com/web/id/99/p/1/pt/7/product.asp). Xantrex has since acquired Heart Interface and replaced the inverter with similar units in the Xantrex product line.
- Isolator: Charles Industries Model 93-BI160/3-A. This is actually a three-battery-bank, one-alternator unit. The two-battery-bank model, 93-BI160/2-A, would have been fine for us.

AUTOMOTIVE CHARGING SYSTEMS

Once installed, our house bank took many hours to charge and often wasn't sufficiently charged even after lengthy cruises. Our ACDelco alternator is advertised to produce 105 amps, plenty to charge our banks quickly. While investigating the poor charging rate, our first discovery was that the alternator frequently produced less than 50 amps. That charging rate is inadequate for a large bank of deep-cycle batteries.

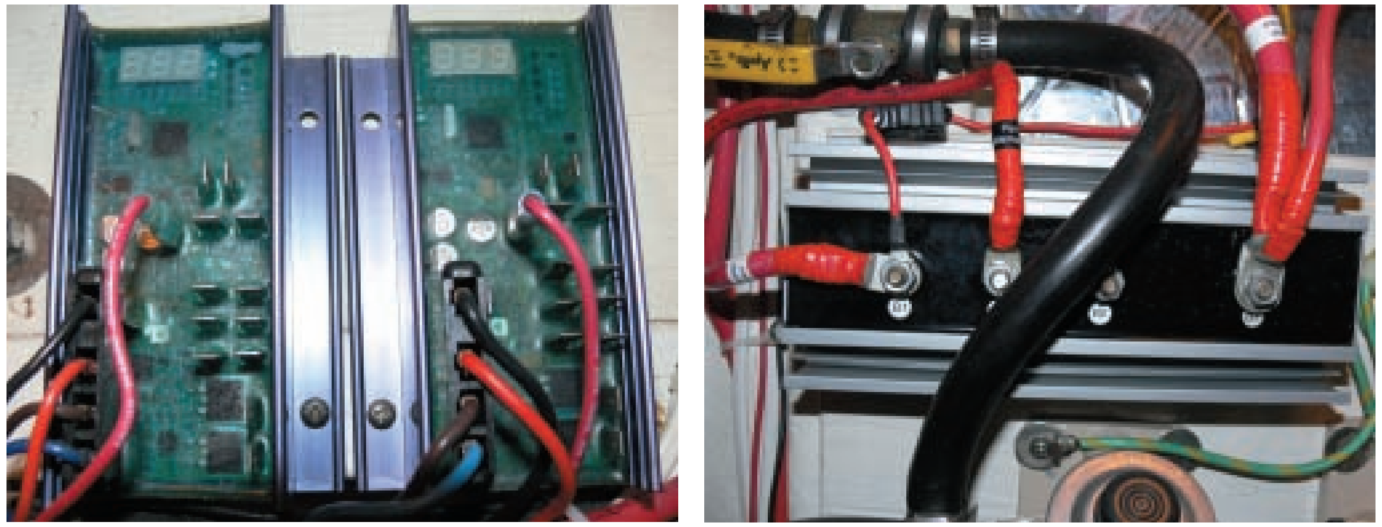
What was wrong? The problem turned out to be the voltage regulator.

To control costs or as a result of ignorance, many boat manufacturers opt not to replace the alternator and regulator that are delivered with most marine engines. These alternator/regulator combinations are designed to charge automotive, truck, or industrial start batteries and are not designed to effectively charge deep-cycle battery banks.

To understand why, consider the difference in usage patterns. Cars typically are driven frequently and discharge little between uses; car batteries rarely fall below a 90 percent charge level. The battery discharges for two to five seconds when supplying current to the engine starter and, after that short discharge period, spends minutes or even hours charging. The average diesel engine, for example, requires less than 1Ah to start. These systems are seldom discharged deeply, and they rarely consume the full-rated output of the alternator. A boat with a deep-cycle house battery bank has a completely different usage pattern. When in use, the duty cycle for a boat's house bank is two to four hours of charging, and then a long, steady discharge to a floor of 30-50 percent.

The voltage regulator that controls alternator output in automobiles is configured to match the automobile usage pattern. It is designed to efficiently charge a lightly discharged starting battery, to supply power for electrical accessories, and to avoid overcharging the starting battery during longer trips. This configuration results in slow charging when used in a deep-cycle application, such as a marine house battery bank. The solution is to rewire the alternator for external voltage regulation. Any electrical repair shop specializing in starter, alternator, and electrical system repair can do this. Then, an external voltage regulator should be installed. A wide variety of brands is available; the key requirements are that the regulator be multistep (three-step charging is typical) and configurable for your battery chemistry (flooded, gel, or AGM). Temperature compensation is also a valuable feature, although we don't use it.

At this point, we've decided on a single large battery bank. We've selected a battery type and bank size, and we've replaced the automotive voltage regulator with an external multistep regulator. Only two tasks remain to be performed: tuning the regulator to avoid charging beyond the continuous charging capabilities of the alternator, and isolating the starting batteries from the house batteries when not charging.



Left: The voltage regulator that controls alternator output in automobiles is configured to match a car's usage pattern. This results in slow charging when used in a deep-cycle application, such as a marine house battery bank. The solution is to rewire the alternator for external voltage regulation. Right: Many people associate isolators with poorly performing charging systems, but often this is due to errors in the isolator's installation. A correct installation charges both banks through a two-bank isolator, with the voltage regulator sense wire attached to the alternator output post. This configuration, with a multistage regulator, will charge very efficiently.

EXTERNAL VOLTAGE REGULATION

This is a lesson we learned the hard way: while manufacturers accurately specify the maximum rated output of their alternators, what they don't always specify is the duration for which the alternator can produce that current. For marketing purposes, they often quote the maximum burst charging rate rather than the continuous rate. At maximum rated output, many alternators used in marine applications will overheat after five to 10 minutes of charging, as you can see from our experience, which follows.

We installed everything and tuned the external regulator to deliver the alternator's full-rated charging current of 105 amps when needed. The charging system was completely transformed; it was working perfectly and charging quickly. But, as we sat back and admired the work, we could smell that something wasn't quite right. We put an infrared heat gun on the alternator case and found that its temperature was 350°F and climbing: the alternator had overheated. We took it back to the local electrical repair shop, where the technician replaced the stator and bearings. (Neither component does well at 350°F.) We needed to avoid another overheating incident, or we'd be back at the shop.

We now knew that 105 amps was simply a marketing number. What we didn't know was the reliable continuous charging rate. What would the alternator charge at safely for hours at a time? This number is critical. If the voltage regulator is adjusted too low, charging times are unnecessarily lengthened. An adjustment that is too high will overheat the alternator.

We decided to explore the limit by calling any alternator manufacturer whose phone number we could find and asking, "Can your alternators put out full-rated amperage continuously?" The reflexive answer was always "yes." We then asked if the manufacturer was comfortable with the alternator charging at maximum rated output even at a temperature exceeding 300°F. With this, there was some hesitation, then: "No, not really." Next, we asked what temperature is the maximum safe level. The numbers ranged from 200°F to 225°F.

Armed with the maximum safe temperature, we used this data and the infrared heat gun to find the real continuous maximum charging rate for our alternator. Our small-frame, 105-amp ACDelco can safely deliver 70–75 amps and can run this way for years.

If it's run much higher, we risk early failure. To prevent the alternator from becoming damaged by overheating, some voltage regulators are capable of

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monitoring the alternator case temperature and adjusting output accordingly.

ISOLATING THE BATTERY BANKS

So, now we have a well-designed house battery bank and an efficient and reliable charging system. All that is missing is a means of isolating the house and starting banks. The two banks must be charged together, but they must be separated during the discharge phase to avoid the risk of a discharged house battery draining the starting batteries to the point that the main engine cannot be started.

The simplest solution is to use a battery switch. When charging, the switch should be set to "both." When at rest, the switch should be set to isolate the starting bank from the house bank. If you forget to switch to "both" when under way, the house bank won't be charged. If you forget to isolate the two at rest, you'll discharge the starting bank and may not be able to start your main engine. We boat in secluded areas, and a manual switch leaves too much room for human error. That leaves two alternatives: an isolator or a combiner.

At one time, an isolator was the most common choice. This is simply a bank of large diodes that allows charging current to flow in one direction and prevents discharge in the other. Isolators are ideal for ensuring that the starting and house banks are being charged together when the engine is running and are separated otherwise. We like isolators because they are simple, can last the lifetime of the boat, and require no service. We believe isolators are the correct solution when balancing all factors, but many people associate isolators with poorly performing charging systems. Therefore, we'll describe the problems that isolator installations can have, discuss an alternative, and then show how a correctly installed isolator can yield a high-performance, nearly maintenance-free system.

The problem with isolators is that they dissipate or absorb about 0.75 volt. (They convert this energy to heat; hence their typically large heat sinks.) This can reduce overall charging speed and efficiency. In order to quickly charge flooded lead acid batteries, the charging voltage needs to ramp up to roughly 14.5 volts toward the end of the charging cycle. If the alternator produces this voltage and the isolator reduces it to around 13.75 volts, charging will be extremely slow for the latter portion of the cycle. It won't work effectively. Understanding this issue, we went looking for better solutions and tried a combiner.

Combiners essentially are large, electronically controlled relays. They close a circuit that joins the house and starting batteries when charging and open the circuit at all other times. To avoid fire risk, the combiner must be rated to handle the highest possible alternator power. This means that large, continuous-use relays are needed; the resulting units are several times more expensive than isolators. But a relay doesn't reduce the voltage as an isolator does, so, to us, a combiner seemed the ideal solution.

After installing a suitably sized combiner, we were very happy with the charging system, and it ran well for more than a year. When cleaning up our engines one day, some water got into the combiner control box, and that was it. The electronics no longer functioned. After an expensive replacement, we were back to 100 percent charging efficiency. We ran like that for several more years before one of the relays developed excess resistance and overheated to the point of becoming a fire risk.

Our conclusion is that combiners *can* work well, but they are service intensive and somewhat fragile. They are electromechanical devices and can stick closed, stick open, and have a variety of other failure modes. They can arc and build up resistance over time, and this can lead to excessive heating. We don't like failure modes that involve dangerous overheating or an inability to charge. Fortunately, an alternative exists. Isolators can be made to perform well despite the nearly 0.75-volt loss for which they are frequently criticized. And, if the isolator is sized and installed correctly, few things on a boat will be more reliable.

When isolators are blamed for poorly performing charging systems, the problem can often be traced to one of two installation errors. The first is the less common of the two. In this misconfiguration, the start and house battery banks are connected through an isolator, and the alternator directly charges the starting bank. The problem is that the starting battery bank will be charged at nearly 0.75 volt higher than the house bank. Either the starting bank is charged correctly and the house bank is undercharged, or the house bank is charged correctly and the starting bank is overcharged.

The correct installation uses a two-bank isolator and charges both banks through the isolator. The alternator is attached to the center post (usually marked "A"), and the two battery banks are connected to the outer terminals (often marked "B," or "B1" and "B2"). In this configuration, the charging voltage sent to the house and starting battery banks is the same. This does not result in an overcharge of the start bank during the lengthier house bank charge, because the start bank's typically higher charge state yields increased internal resistance to charge acceptance (both banks must be of the same chemistry).

The second installation error is the one that originally caused us to be dissatisfied with the charging efficiency of isolator-based systems. In this misconfiguration, the voltage regulator sense wire is attached directly to the alternator output post, rather than to a battery bank. The voltage regulator adjusts the alternator output based on feedback from the sense wire. When the sense wire is attached to the alternator post, it reports a nearly 0.75-volt higher charge than what the batteries are actually receiving (due to the voltage loss across the isolator), and the batteries are chronically undercharged. The correct installation positions the sense wire at a battery bank, "after" the isolator. The voltage regulator will then adjust the alternator voltage upward to account for the loss. It's almost as if the isolator isn't there at all.

FOR MORE INFORMATION

To learn more about marine charging systems, an excellent resource is:

- *Boatowner's Mechanical and Electrical Manual* by Nigel Calder, International Marine/Ragged Mountain Press, third edition.

This second installation error is common in boats originally built using a battery switch rather than an isolator. Since the battery switch introduces little resistance, sensing the battery voltage at the alternator output works as well as sensing at a battery bank. Nearly all external regulator manufacturers stress the importance of installing the sense wire *at* the battery bank, as a voltage drop of just 0.1 volt can have a significant effect on charge efficiency. Nonetheless, this is a common misconfiguration.

On boats that were built with external regulation or where external regulation was later added, the alternator output is often selected as a convenient, but less than ideal, voltage regulator sense point. Some installation diagrams even recommend this location. However, when an isolator is added between the alternator and the battery banks, this easy sense point is no longer the right choice.

Moving the voltage regulator sense wire to a battery bank solves the problem. Automotive charging systems with built-in voltage regulators all sense voltage at the alternator output and don't work well with isolators. Again, external regulation is the recommended solution.

With a correctly installed isolator, the banks are fully isolated when not charging, the charging rates are on specification, and the system is highly reliable. A properly designed isolator-based system is nearly indistinguishable in charging performance from a combiner-based system, and isolators are both cheaper and less service intensive. We like systems that work well year after year and that don't require service, replacement, or have potentially risky failure modes.

An industry-accepted alternative calls for sending all charge output from the alternator to the house bank, then siphoning a small, regulated charge from the house bank and sending it to the start battery. Several devices are available for doing just this.

MISSION ACCOMPLISHED

The charging system we ended up with is based on a properly sized battery bank, an alternator with external regulation, and an isolator. External regulation allows us to obtain the maximum rated continuous output that our alternator was designed to deliver. The isolator delivers full charging rate to both battery banks and keeps the banks separate during discharge. The overall system is simple, efficient, and nearly maintenance free. (Of course, the batteries still need to be inspected and maintained with water, and the alternator belt tension needs to be checked.)

As you configure or update your boat's system, we hope that this information will help you avoid some of the U-turns we took on the path to creating an efficient and reliable charging system.