THE BIG BATTERY BANK EQUATION

Story And Photography By Steve D'Antonio

In part one of this article we discussed electrical safety, as well as battery security and installation requirements. In part two, we'll discuss over-current protection, fuse and circuit breaker requirements, as well as preferred connection methods and wiring protocols.

A variety of factors must be taken into consideration when designing and installing any battery bank. As mentioned previously, for those involved in designing, installing, and inspecting large battery banks, or if you are tasking others to do so, standards set forth by ABYC on this subject are well worth review, particularly those related to over-current protection or fuses and circuit breakers (hereafter referred to as OCP). While the standards may not reflect the needs of large battery banks in particular, they remain fully applicable for much of the wiring associated with battery banks and of course DC systems in general. Interestingly, the U.K.'s Recreational Craft Directive or RCD, a program loosely similar to that of our ABYC, is in the midst of revisions that will take into account the special needs of large battery banks.

ELECTRICAL CONSIDERATIONS

Battery banks and their connections to the vessel's electrical system often fail to meet OCP guidelines. All cables leaving positive battery terminals or positive bus bars, unless used or capable of being used for starting purposes, must have OCP within 7 inches of the source. If cabling is contained within sheathing, a conduit, control box, enclosure, etc., OCP may be located 72 inches from a battery terminal or 40 inches from a battery switch or other terminal, bus bar, etc. In all cases, OCP should be installed as close as possible to the source of power—72 inches and 40 inches are maximums. This guideline includes cabling used for battery chargers and inverters, two components that I often find lacking in any OCP, or if present, it's installed incorrectly.

Because large battery banks possess vast quantities of reserve energy, OCP guidelines are especially important. A short circuit in a heavy gauge cable that is connected to a large battery bank positive post(s) or bus bar will result in significant heat generation and almost

Above: The old rules no longer apply; as battery banks become larger, to meet the burgeoning electrical needs of cruising vessels, the manner in which they are designed and installed requires a fresh approach.

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certainly a fire in the presence of combustible material. Thus, with the aforementioned exception for starter circuits, all positive cabling that is attached to large battery banks must be afforded the protection of appropriately sized OCP (see the sidebar on page 56 on this subject).

If the large bank plan includes the option for engine start (the above-mentioned exception) paralleling, separate cabling should be used for this function rather than utilizing house supply cabling, which would undesirably necessitate, or at least allow under ABYC guidelines, the elimination of the OCP on some or all of the supply cables that are connected to the bank's positive terminals. That's a lot for many installers, surveyors, and electricians to get a grip on. However, the goal is to minimize the length and volume of cables that are attached to large battery banks that lack OCP. There's talk within the industry of recommending OCP on starting circuits. Perhaps, with the advent of a variety of easily installed OCP hardware and more data, the time has come for this approach or at least for its reconsideration.

Battery temperature is a frequently overlooked side effect of large bank installations. Without adequate ventilation, batteries in the center of the "pack" often overheat.

Additionally, if a bank is made up of multiple groups of paralleled batteries or "strings" then each of these should include OCP (over-current protection for individual batteries within a string remains an option too), as well as a disconnect switch. The latter enables the user or service personnel to isolate groups of batteries from a large bank for troubleshooting or service purposes, or in the event of an individual battery or cable failure. A master disconnect for the entire bank remains desirable in that it would enable a user to quickly disconnect the bank from the vessel in the event of a fire or other malfunction. Master disconnect switches should be located in readily accessible locations, preferably outside engine rooms. Under no circumstances should it be necessary to move gear or remove screwed-in place panels to access them. They should not be located directly above a battery bank.

WIRING PROTOCOLS

In the opening paragraphs in part I of this article, I mentioned the temptation to simply increase the scale of an existing system or technology—the "more of the same please" approach. In no aspect of large battery bank design is this caveat more relevant than the wiring protocol. In the vast majority of large banks I encounter, multiple batteries are simply wired in parallel, either in a long string, or randomly interconnected. The risk of connecting exceptionally long strings is that it often leads to an intra-bank voltage imbalance.

Perhaps one of the most commonly misunderstood wiring protocols is the end versus cross-connection protocol. This involves the method by which a large battery bank is connected to the vessel's electrical system. Imagine a series of three or four 12-volt batteries connected in parallel, all lined up (with air gaps between them); each of the batteries' like terminals are interconnected, positive to positive and negative to negative. At the physical end of the bank (at one of the batteries), positive and negative cables from the vessel's electrical system are connected for convenience sake and to minimize cable length. While this approach is commonly encountered, it can be exceptionally detrimental to the bank as a whole. Because resistance within the bank is cumulative, batteries further from the main connection point tend to provide power disproportionately (i.e., they are cycled less). The result is the batteries "wear" at different rates, creating voltage imbalances within the bank—imbalances that reduce its effective capacity.

The preferred alternative to this approach simply calls for making positive and negative connections at opposite ends of the bank (i.e., at the batteries at either end of the string). Doing so reduces the potential for intra-bank imbalances. The next step in this process involves the connection approach for the bank's primary charge source. It too should be cross-connected. However, the cross should mirror rather than parallel the connection for the bank's supply to

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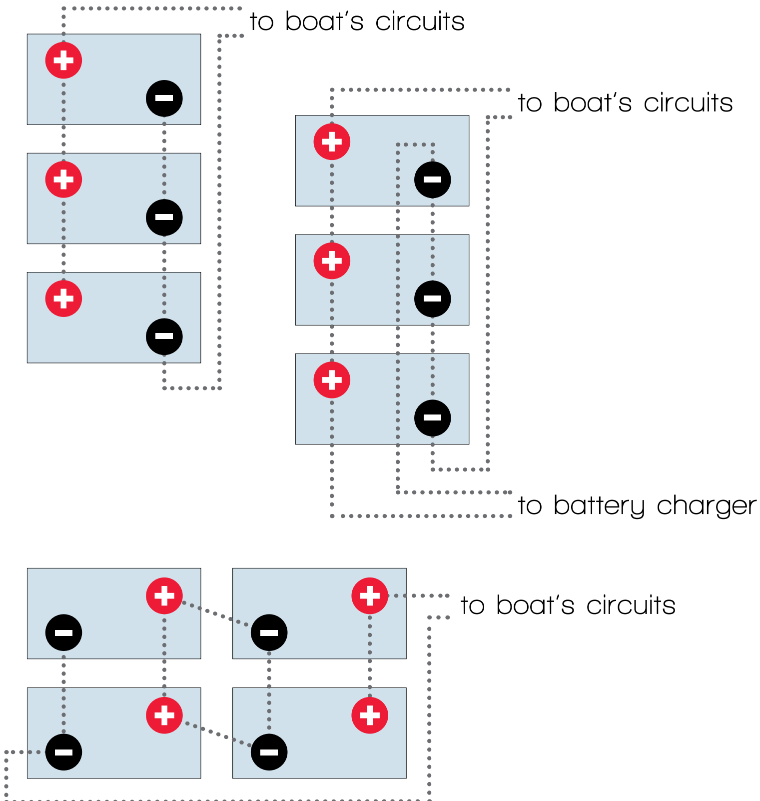

Where possible, wiring battery banks so that loads are drawn from opposite ends of the bank, and mirroring charge source inputs, can increase battery longevity.

the house. Using this protocol, while a charge source is present, the battery bank will act as a buffer between heavy loads such as windlasses or inverters and chargers/alternators.

While there are exceptions to every rule and even debate within the industry, many battery manufacturers agree that the maximum number of batteries that should be paralleled is between three and four, and some sources say five. Having said that, it is likely the most frequently violated "rule" for cruising vessel battery banks. I've seen as many as ten 12-volt batteries connected in parallel, seemingly working well for years. The risk is, once again, intra-bank voltage imbalances and their destructive, life-shortening nature.

While smaller case sizes are convenient and certainly easier on the installer's back, they are less than ideal. To minimize the overall number of batteries in a string when paralleling, it's preferable to utilize fewer batteries of a larger case size rather than a greater number of smaller batteries. Doing so minimizes both imbalances and the quantity of connections that invariably increase resistance.

As all marine electricians know, batteries within a bank may be connected in either parallel or series, or a combination of both. As one might expect, there are pros and cons to each

When paralleling batteries, fewer larger case sizes make sense. However, using multiple lower voltage batteries connected in series offers benefits as well.

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Left: When monitoring battery banks, and in some cases even an individual battery, charge and discharge rates provide the user with an indication of the system's and batteries' health. Right: Poor connection practices like this should be avoided in any battery installation, however, weaknesses are exacerbated in large banks because of their significant fault current potential.

with neither winning clear favor. Paralleling banks is relatively easy. Each battery adds its amp hour capacity to the bank with no change in voltage, and common case sizes and voltages can be used. The drawbacks to paralleling are the aforementioned voltage imbalance issue and the resultant theoretical limit of three or four batteries per string or bank. Additionally, while a defective battery within the bank can draw current from the others, and potentially overheat, it can also be removed from the bank with the effect being a reduction in capacity but no change in voltage.

Batteries connected in series, on the other hand, present their own set of advantages and disadvantages. Ideally, and because batteries that are connected in series behave as one large battery and thus have no theoretical string limit other than the desired voltage, interconnecting a greater number of lower voltage individual batteries in series will provide the user with appreciable bank capacity without the intra-bank voltage imbalance issue. Large battery bank installations often use such an approach very successfully.

However, perhaps the greatest single weakness of large banks utilizing series connections is the old-fashioned Christmas tree light failure scenario: If a single battery fails in a series bank, the entire bank is brought down with it, and the offending battery cannot be removed from the bank, unless a replacement is available (ideally, the "spare" would have to not only be maintained at its parent voltage, but also be of the same cycle "age" as the rest of the bank, which is simply impractical) because doing so would change the bank's voltage output.

A variation on the series/parallel theme involves utilizing strings of series banks, each producing the desired voltage for the vessel that are then connected, in parallel, to a single bus bar. Such an arrangement can produce significant amp hour capacity, likely well within the four-string maximum, while each series string behaves as if it were a single, large battery. Whichever arrangement is chosen, it's important to ensure that the resistance in the cabling between and amongst the banks is kept to a minimum and consistent. If multiple strings are connected to a central bus bar, variations in resistance will cause charge and discharge imbalances.

With larger battery banks that utilize multiple parallel strings, it's virtually impossible to know the health or condition of any given string. Monitoring the temperature of individual batteries may provide an indication of an impending problem. Temperature monitoring of individual batteries and banks is valuable and often available as an adjunct to some voltage and amp hour monitors, as well as whole vessel monitoring systems. However, unless the fault is pronounced it's not very effective. Subtle problems are far more reliably detected using current monitoring; multiple Hall effect current sensors will provide a clear picture of a string's discharge and charge acceptance rates, which can then be compared to its brethren in the bank. Ideally, multiple strings should provide and accept the same or nearly the same current to the house bank and from charge sources respectively. A disparity may be an indication of a failing battery or simply a corroded

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LARGE BATTERY BANK OVER-CURRENT PROTECTION CONSIDERATIONS

Protecting the cabling involved with any battery bank is vitally important from a safety and fire prevention point of view. Large battery banks, because of the potential fault currents involved, add a few twists. When designing, installing, and servicing these banks, it makes sense to keep in mind their potential for significant fault current generation. I discussed this subject with Wayne Kelsoe, vice president of electrical engineering for Blue Sea Systems, manufacturer of a wide range of high-quality marine electrical gear. Wayne has compiled information and conducted experiments on this subject for both Blue Sea Systems and ABYC for the purpose of offering components that are capable of handling large battery bank current and for generation of revised standards respectively. I've distilled some of the information he provided in our correspondence:

• The potential fault current for batteries connected in parallel is nearly cumulative and is only mitigated by the resistance of the related wiring and connections.

• Fault current is often more than four times the cold cranking amp rating and for a safety margin, assume five times. That is, while a single flooded 8D can typically produce about 1200 cold cranking amps, it has a potential fault current of 5000 amps (more for an AGM) and the need for OCP that carries an ampere interrupt capacity or AIC of at least this amount.

• There is a loose correlation between conventional battery weight and fault current (and amp hours and fault current). Batteries that rely on thin plate pure lead (TPPL) designs can deliver 67 amps per pound at 12 volts, while others are closer to 37 to 45 amps per pound at 12 volts. As a rule of thumb, in the absence of other data, multiply the weight of a 12-volt bank by 50 for an indication of potential fault current. The correlation between fault current and amp-hours figures range from a high of 89 amps per rated amp hour for TPPL batteries to 20-25 amps per rated amp hour for others. This should be considered a rough calculation at best. These ampere figures can be halved for 24-volt systems.

• Disconnect switches should be located where they will benefit from OCP as few, if any, are capable of safely carrying full-fault current without suffering permanent damage.

• Banks larger than a single 8D, a pair of GP31 batteries or six 6-volt golf cart batteries should rely on a Class T fuse for OCP (author's emphasis). These fuses are rated at 20,000 amps at 160 volts and should handle 100,000 amps at 32 volts. While circuit breakers can be used, provided they carry the appropriate AIC, a common failure mode after a short circuit fault is for the contacts to fuse together when reset after such a fault. If the fault still exists, and this isn't an unusual scenario (many have reset a circuit breaker after it trips the first time without investigating the cause), then no effective OCP may exist and a fire could ensue. At the very least, the breaker will be internally damaged (they often include a fusable link of a sort that will open in the event of an extreme "bolted" rather than incidental short), and it will not reset and the circuit will remain open. Vessel operators often carry spare fuses, but how many carry spare primary circuit breakers?

or loose connection. In any case, such an arrangement provides the user with a valuable early warning tool for a possible impending failure.

It's an oft-repeated battery bank axiom—avoid mixing case sizes and ages. In theory, different case sizes present differing internal resistance even when new. When connected to other batteries, either in parallel or series, these differences can push a bank into imbalance. The same is true of batteries as they age and cycle, their resistance changes and thus replacing one battery in a bank that has been cycled hundreds of times means it will almost certainly create a charge/discharge imbalance, the effects of which are difficult to predict.

Similarly, under no circumstances should differing battery types (i.e., flooded and SVRLA) be arranged in such a way as to be charged or discharged as part of the same bank. The charge profile, internal resistance and thus, charge acceptance rate of an SVRLA differs markedly from that of a flooded battery. Therefore, they should not be paralleled except momentarily, for emergency starting purposes for instance. Ideally, all batteries/banks aboard should be of the same type (i.e., SVRLA or flooded) and the same voltage, including propulsion engine and generator start batteries. With this approach, emergency paralleling and charging are simplified and more versatile.

Purpose-made deep-cycle batteries are often available with a variety of different terminal styles, from posts and flags, which are usually made of lead, to threaded inserts and "L" blades, which are often copper. Whichever type of connecting hardware is used, it's important to ensure that sound low-resistance connections are made and that large gauge cabling does not overload the terminals. Ideally, no more than two ring terminals should be installed at any single battery post (ABYC's guideline on all ring terminals is four per stud, however, the limit of two at batteries is my own preference).

Where offered, copper alloy terminals are preferred as they are less prone to deformation, denting, and breakage. If the terminal's surface is other than smooth and flat, resistance may be greater where

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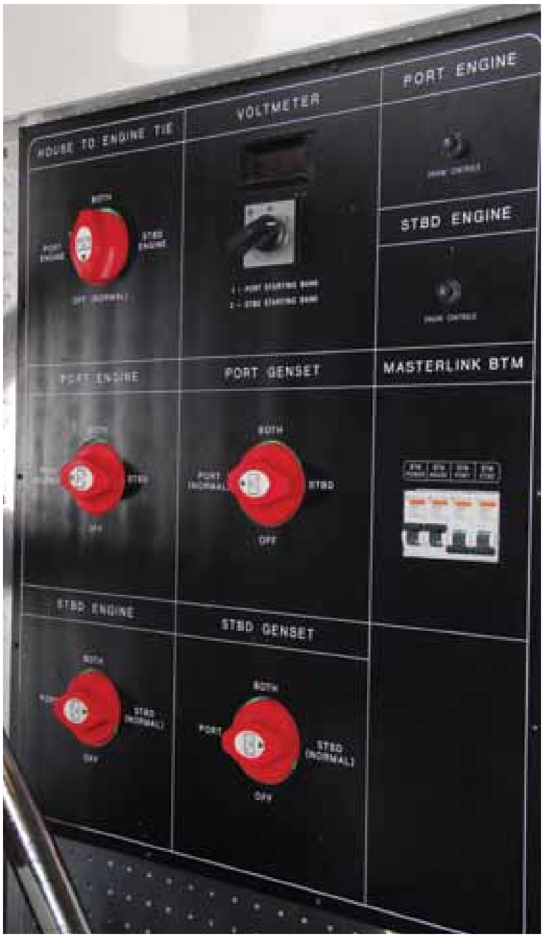

Being able to isolate battery banks, or "strings" of batteries within a large bank, is a prerequisite. Main isolation switches should be readily accessible.

it interfaces with a ring terminal. Common lead posts require some form of conversion to a stud connection that will accept a ring terminal. Avoid adapters that utilize cast in place studs as these are prone to stud separation, especially when using heavy cables. Instead, use adapter terminals that rely on through-bolt fasteners, all of which impart compression rather than tension loads on the adapter body. It may be necessary to add supplemental support to cables to remove some load from the battery's terminals. Finally, where flooded batteries are concerned, route cables in such a way as to avoid impeding access to cell fill caps.

Ensure that all connections are direct, and avoid any intervening hardware and components, especially stainless steel washers, lock washers, or fasteners. Ring terminals must make direct contact with battery terminals. The fastener is there merely for

CASE STUDY

I recently inspected a vessel, and according to the manufacturer, it carried an ISO Ocean A rating. The description of this category states that vessels carrying this rating are "designed for extended voyages where conditions may exceed Force 8 [Beaufort] winds (34–40 knots, fresh gale force) and significant wave heights of 4 meters (13 feet) and above, and vessels are largely self sufficient." The term "significant wave heights" bears some elaboration as it can be misleading; it is the average of the highest one-third of the waves. It does not take into account shoaling or currents—two factors that are responsible for increased wave heights. Many oceanographers agree that during a 24-hour period in open ocean conditions, it's likely that one will encounter a wave twice the significant wave height, or in this case, 26 feet. Having experienced these conditions, I can confidently say they test both the design and execution of the systems aboard any vessel, including that of battery banks. In fact, in my experience much more benign conditions have been responsible for wreaking systems havoc aboard poorly found vessels.

Because the vessel carried such a rating, and because it therefore implied that it would be used in bluewater, offshore, "Ocean A" conditions, I paid particularly careful attention to all critical systems—steering, shift and throttle controls, engine, running gear and generator installation, watertight integrity and the installation of the battery bank. In this case, two banks were made up of twelve 2-volt batteries each. The batteries lacked any visible labeling, a problem in and of itself. However, I estimated they weighed approximately 90 pounds. Thus, each bank as a whole weighed roughly 1,000 pounds. Per bank, the cold cranking amp capacity was likely in the region of 2,500 amps, which could yield a theoretical fault current of over 10,000 amps. Yet, the banks rested on sheets of otherwise unreinforced, poorly supported 5/8-inch plywood and were secured using web straps and plastic buckles, each of which encompassed an entire row of five batteries (there were two batteries adjacent to the main bank of ten). The straps passed under the batteries and therefore, the method that was used to secure them to the shelf, assuming they were secured, was impossible to determine. Each bank was located within a locker or cabinet of sorts; it was constructed of plywood. The batteries were surrounded by a low "wall" made of removable high-density polyethylene planks; I was able to slide sections of it out—it lacked any fastenings. The primary fuse for each bank was of the ANL variety.

For a vessel of this type, one that was clearly designed for bluewater, offshore passagemaking, I deemed such an installation as inadequate at best. If the vessel were to roll heavily, it's possible that the battery banks could have broken out of their corals en masse and slid across the deck area located between them. The point is, if the expectation is that a vessel will venture offshore, that it may be subject to heavy weather, the installation must be in keeping with the overall capabilities of the vessel rather than potentially ending up as the weak link in an otherwise sound design.

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support and to impart compression. It's not designed to be nor should it be used as a current carrying conductor.

A common error on the part of otherwise well-meaning installers involves the interspersing stainless steel washers between cable ring and battery terminals. Steel and stainless steel's conductivity is significantly less than that of electrical grade copper for an equal area, and as such, it creates appreciable resistance to the flow of electricity, and a consequent generation of heat. The scenario is particularly insidious in that the heated washer expands when loads or charge current are present, and then cools and contracts when the system is dormant, then heats and expands again, and so on. This often leads to a loosening of the connection and to a further increase in resistance, which generates more heat cycling and arcing. If any hydrogen gas is present, the ingredients for a battery explosion now exist. You get the point—steel and stainless steel washers or other hardware should never be placed in the current path anywhere in a large battery bank system or its associated wiring. Similarly, bus bars and other termination points used in such systems should be, unless purpose-made and rated for the application, fabricated from pure, electrical grade copper, rather than stainless steel, brass, bronze, or aluminum.

Installation of ring terminals, battery post adapters, and other hardware and components within and around large battery banks benefit from careful attention to detail; this includes the use of a torque wrench when making connections at batteries (most battery manufacturers include torque specifications, particularly where permanent threaded inserts are used), application of conductive paste to contact surfaces, and coating completed connections with corrosion inhibitor.

Additionally, components such as fuses and circuit breakers, disconnect switches, and bus bars should be clearly and permanently labeled. Also, consider preparing diagrams of the bank and its wiring—they need not be full-blown schematics, just a clear indication of the gear that's installed, the routing of the wiring, and the presence and location of fuses and switches, etc. A copy should be posted at, or stored adjacent to, the battery bank, and another copy should be kept in your own files, preferably electronically, so it can be emailed if necessary. If your system didn't come with such a schematic (ask for one if you are having a boat built or undergoing a refit), one can be prepared after the fact.

Large battery banks present the designer, installer, service personnel, and vessel owner with a series of challenges, and in some cases the rules remain to be written or rewritten. Begin by ensuring that banks are mechanically secure and electrically safe, then aim to enhance reliability and efficiency. Finally, be certain that you possess a thorough understanding of your system and are well versed in using and maintaining the bank properly.

Because of their extremely high interrupt capacity, class T fuses are well suited for use with large battery banks. ANL fuses, on the other hand, possess a much lower interrupt capacity and as such are less than ideal in this application.

Steve owns and operates Steve D'Antonio Marine Consulting (www.stevedmarine.com), providing consulting services to boat buyers, owners, and the marine industry.

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