



**THE MARINE
ELECTRICAL
&
ELECTRONICS
BIBLE**

**John
C.
Payne**



**A Professional Practical Handbook
For Cruising Yachts**

THE MARINE ELECTRICAL AND ELECTRONICS BIBLE

**A PROFESSIONAL MANUAL FOR CRUISING YACHT ELECTRICAL
AND ELECTRONICS SYSTEMS**

JOHN PAYNE

This book is for my mother Pam, who stayed at home as my father and I pursued our seagoing careers, and tolerated us at home as we messed about in our boats.

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J C PAYNE

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Wayworld 45,

Navigation station with full electrical & electronics fitout.

BOC Challenger "Buttercup" (Photo by Gregory Haremza).

Skipper Don McIntyre.

Stern mounted wind generators, solar panels and aerials.

FOREWORD

Think of your electrical system as parts of the body - arteries, veins and capillaries (wires) providing blood (electricity) to all areas of the body (boat). If you wish to keep your boat healthy and safe you must have an electrical system based on sound principles.

As a competitor during the 1990/91 BOC challenge solo around the world yacht race, I had, on many occasions to witness potentially life threatening dramas being played out on fellow competitors yachts. Deep in the Southern Ocean, amongst icebergs and raging gales, simple electrical problems snowballed into potential disasters. It is just as easy to experience your own life threatening drama out in the bay or on some quiet backwater if your electrical system is not up to standard.

I have known John Payne for many years, his professional reputation a by-product of an exhaustive professional career so it was understandable that all three Australian BOC competitors (myself included) sought his advice and involvement for on-board charging and electrical systems, which went on to function efficiently under the most demanding conditions.

Whilst the BOC is only for a select few, the experience gained is of benefit to all cruising or professional mariners.

This publication is of real value to every boating person. If you are a builder it lays the foundations; if you are employing a professional marine electrician, it will give you an insight into why he does certain things and if you have bought your boat and plan to set sail, it will become a bible for maintenance and repair when no one else can get to you!

To stop blood flow to any part of your body would have disastrous consequences!

This comprehensive publication can be the key to your healthy boat.

Don McIntyre

McIntyre Marine Services

"Sponsor Wanted/Buttercup"

2nd Class II, BOC Challenge

28,000 Miles in 153 days,

12 hrs, 21 mins, 20 secs.

ABOUT THE AUTHOR

The author has been a professional marine electrical engineer and technical author for over 18 years. His career has spanned a number of years in the merchant navy, offshore diving and oil exploration industry.

In the merchant marine he sailed under several national flags, serving on British tramp freighters, German and American fully automated refrigerated cargo vessels, oil tankers and Pacific Islands passenger cargo vessels, both as an engineer and as a marine electrician.

In the offshore oil industry he was employed in senior marine electrical positions on some of the worlds most advanced off-shore oil exploration installations, both American and British, in the UK North Sea and the Mediterranean.

As a qualified technical author, he is frequently involved in the preparation and writing of various marine electrical and electronics equipment maintenance and operations manuals, both civilian and defence. He regularly lectures on the subject of marine electrics, and has been published in several yachting magazines.

The author has also run a successful marine electrical business specialising in marine power systems. The author cruises regularly and is a member of the UK Cruising Association, Royal Yachting Association, and is a Member of the Institute of Diagnostic Engineers.

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INTRODUCTION

The average cruising yacht now has a sophisticated and ever increasing range of electrical and electronic equipment fitted. The electrical system required to support this equipment has been a largely ignored subject, and is rarely treated as the foundation for reliable equipment operation.

The majority of magazine articles and books that do attempt to describe the subject frequently end in simplistic overviews or tracts of recycled equipment advertising material, but rarely is conclusive advice given. In most cases, the writers simply do not understand the theories involved. More often than not books and articles are written by armchair experts and people without any formal electrical qualifications or experience, or a limited understanding of the range and complexity of marine electrical and electronics problems. The credibility of writers often appears to be based on the descriptive use of abstract theories or the use of a range of analogies, which appear to be mostly about plumbing, to explain themselves, and it is probable that they themselves can understand in those terms only. All this theory and jargon has had the reverse effect of confusing the reader by over-complication of the subject with much of the information either technically flawed or contradictory. The general result is confusion for the reader, bad practices, and a resultant degradation of vessel seaworthiness.

Reliable installations require a systems approach, sound planning, equipment compatibility and systems simplicity. These are the basic laws of cruising, for all equipment.

This handbook meets the real and practical requirements of the cruising yacht owner. By overwhelming demand, electrical theory is covered only to a level sufficient to properly select, install, operate, maintain and fault-find with a minimum of technical expertise. Specifically I have set out to destroy the dangerous illusion that vessel and automotive systems are synonymous, excepting the voltage levels. As we all know, there are no 24 hour road services off-shore, and safety therefore depends on sound systems design and installation.

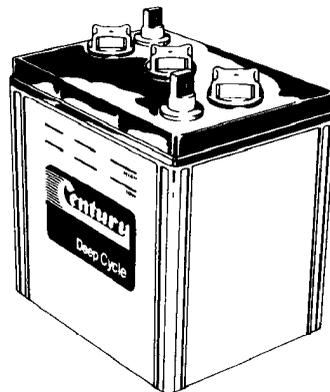
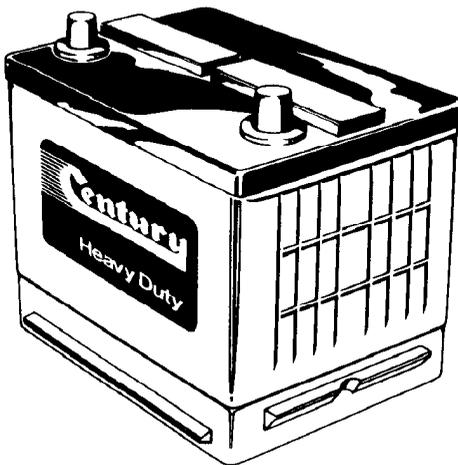
This book encapsulates 18 years of professional experience on merchant vessels, off-shore oil installations, diving support/salvage vessels, cruising yachts, power and work boats. I have attempted to include all the up to date technologies and answers to the hundreds of questions I am asked by yachtsmen every day of every year.

Contrary to popular belief, electrical problems are not an inevitable part of cruising. An acceptable level of reliability is possible. I cannot over stress the importance of adopting a keep-it-simple approach to electrical systems, and also with the installation of electronics. It is easy to be drawn into that vortex of complicated, high tech equipment, but in the end, successful cruising depends on reliability, and that relies on simplicity.

BATTERIES

1.1. Batteries. The heart of any vessel power system is the battery. It has a primary role as a power storage device, and a secondary one as a "buffer", absorbing power surges and disturbances arising during charging and discharging. The battery remains the most misunderstood of all electrical equipment. In the majority of installations it is improperly selected and rated, with a resulting decrease in vessel seaworthiness. For a system to function correctly, the power system must be able to provide power reliably and without disturbance. The following chapters explain all the factors essential to the installation of a reliable power system. Battery types are expanding and the following types are examined:

- a. **Lead Acid Batteries.** The lead-acid battery is used in the majority of marine installations and therefore will be covered extensively.
- b. **Nickel Cadmium Batteries.** These batteries are usually found on larger cruising vessels and are a viable alternative to lead acid batteries.
- c. **Low Maintenance Batteries.** These batteries are often considered and the viability of these is covered.
- d. **Gel Cell Batteries.** Gel cell batteries are a relatively new battery type and their suitability for cruising applications will be analysed.



1.2. Battery Safety. The lead-acid battery is used on the majority of cruising vessels. It is potentially hazardous and the following safe handling procedures should be used:

- a. **Gas.** Battery cells contain an explosive mixture of hydrogen and oxygen gas at all times. An explosion risk exists at all times if naked flames, sparks or cigarettes are introduced into the immediate vicinity.
 - (1) Always use insulated tools.
 - (2) Cover the terminals with an insulating material to prevent accidental short circuit. Watchbands, bracelets and neck chains can accidentally cause a short circuit.
- b. **Acid.** Sulphuric acid is highly corrosive and must be handled with extreme caution. If there is never a need to refill a battery with new acid on yachts:
 - (1) Wear eye protection during cell filling.
 - (2) Wear protective clothing.
 - (3) Avoid splashes or spillage's as acid can cause skin and clothing burns.
 - (4) If acid splashes into eyes, irrigate with water for at least 5 minutes. Seek immediate medical advice. Do not apply medications unless directed to do so by a physician.
 - (5) If electrolyte is accidentally swallowed, drink large quantities of milk or water, followed by milk of magnesia. Seek immediate medical attention.
- c. **Manual Handling.** Observe the following when handling:
 - (1) Always lift the battery with carriers if fitted.
 - (2) If no carriers are fitted lift using opposite corners to prevent case distortion and electrolyte spillage.
- d. **Spillage's.** Electrolyte spillage's should be avoided:
 - (1) Spillage of electrolyte into salt-water generates chlorine gas.
 - (2) Neutralise spillage's immediately using a solution of baking soda.

1.3. Lead Acid Batteries. The fundamental theory of the battery is that a voltage is developed between two electrodes of dissimilar metal when they are immersed in an electrolyte. In the typical lead-acid cell the generated voltage is 2.1 volts. The typical 12 volt battery consists of 6 cells which are internally connected in series to make up the battery. The primary parameters of a lead acid battery consist of the following:

a. Cell Components. The principal cell components are:

- (1) Lead Dioxide (PbO_2) - positive plate active material.
- (2) Sponge Lead (Pb) - negative plate material.
- (3) Sulphuric Acid (H_2SO_4) - electrolyte.

b. Discharge Cycle. Discharging of the battery occurs when an external load is connected across the positive and negative terminals. A chemical reaction takes place between the two plate materials and the electrolyte. During the discharge reaction, the plates interact with the electrolyte to form lead sulphate and water. This reaction dilutes the electrolyte, reducing the density. As both plates become similar in composition, the cell loses the ability to generate a voltage.

c. Charge Cycle. Charging simply reverses this reaction. The water decomposes to release hydrogen and oxygen. The two plate materials are reconstituted to the original material. When the plates are fully restored, and the electrolyte is returned to the nominal density the battery is completely recharged.

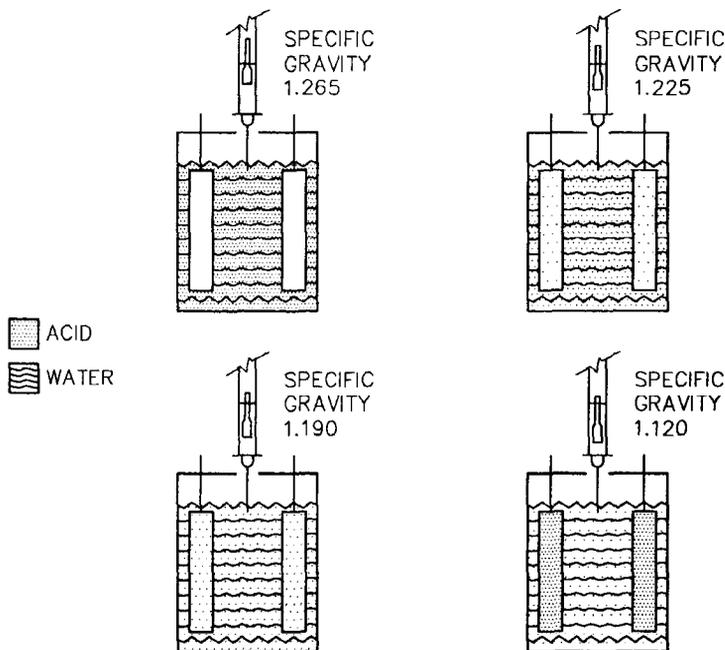


Figure 1-1. Lead Acid Chemical Reaction.

1.4. Battery Electrolyte. The cell electrolyte is a dilute solution of sulphuric acid and pure water. Specific Gravity (SG) is a measurement defining electrolyte acid concentration. A fully charged cell has an SG typically in the range 1.240 to 1.280, corrected for temperature. This is an approximate volume ratio of acid to water of 1:3. Pure sulphuric acid has an SG of 1.835 and water a nominal 1.0. The following factors apply to electrolytes:

a. Temperature Effects. For accuracy, all hydrometer readings should be corrected for temperature. Ideally, actual cell temperatures should be used, but in practice ambient battery temperatures are sufficient. Hydrometer floats have the reference temperature printed on them and this should be used for calculations. As a guide, the following should be used for calculation purposes in conjunction with Table 1-1:

- (1) For every 1.5° C the cell temperature is **ABOVE** the reference value **ADD** 1 point (0.001) to the hydrometer reading.
- (2) For every 1.5° C the cell temperature is **BELOW** the reference value **SUBTRACT** 1 point (0.001) from the hydrometer reading.

b. Nominal Electrolyte Densities. Recommended densities are normally obtainable from battery manufacturers. In tropical areas it is common to have battery suppliers put in a milder electrolyte density, which does not deteriorate the separators and grids as quickly as temperate climate density electrolytes.

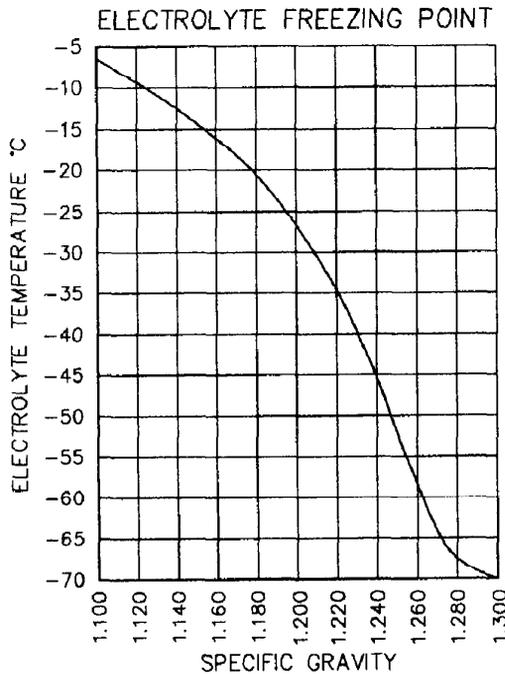


Figure 1-2. Electrolyte Temperature Effects.

1.5. Battery Water. When topping up the cell electrolyte, always use distilled or de-ionised water. Rainwater is acceptable, but under no circumstances use tap water. Tap water generally has an excessive mineral content or other impurities which may pollute and damage the cells. Impurities introduced into the cell will remain, and concentrations will accumulate at each top up reducing service life. Long and reliable service life is essential so the correct water must always be used. Water purity levels are defined in various national standards.

Table 1-1. Electrolyte Correction Table at 20°C.

Temperature	Correction Value
-5° C	deduct 0.020
0° C	deduct 0.016
+5° C	deduct 0.012
+10° C	deduct 0.008
+15° C	deduct 0.004
+25° C	add 0.004
+30° C	add 0.008
+35° C	add 0.012
+40° C	add 0.016

1.6. Battery Additives. There are a number of additives on the market, namely Batrolyte and VX-6. The claims made by manufacturers appear to offer significant performance enhancement. The compounds are specifically designed to prevent sulphation or dissolve it off the plate surfaces. If you read the fine print on one brand, it is not recommended for anything other than new or near new batteries. If the additive is to dissolve sulphates on battery plates, it will be only on the surface, as plate sulphation occurs through the entire plate, so only a partial improvement is achieved. Recently a friend of mine arrived back after an extended Pacific cruise and called over a charging problem. I had installed a TWC Regulator three years previously and he had managed the entire period as a live-aboard without a problem, until he put in an additive. My advice is to leave the stuff alone, your battery electrolyte should remain untouched, just make sure the battery is properly charged and you won't need to resort to such desperate measures.

1.7. Battery Ratings. Manufacturers often quote a bewildering set of ratings figures to indicate battery performance levels. When selecting a battery it is essential to understand the ratings and how they apply to your own requirements. The various ratings are defined as follows:

- a. Amp-hour Rating.** Amp-hour rating (Ah) refers to the available current over a nominal time period until a specified final voltage is reached. Rates are normally specified at the 10 or 20 hour rate. This rating is normally only applicable to deep cycle batteries. For example a battery is rated at 84 Ah at 10 hr rate, final voltage 1.7 Volts per cell. This means that the battery is capable of delivering 8.4 amps for 10 hours, when a cell voltage of 1.7 volts will be attained. (Battery Volts = 10.2 V DC).

- b. **Reserve Capacity Rating.** This rating specifies the number of minutes a battery can supply a nominal current at a nominal temperature without the voltage dropping below a nominated level. This rating is normally only applied in automotive applications. It indicates the power available when an alternator fails and the power available to operate ignition and auxiliaries. Typically the rating is specified for a 30 minute period at 25° C with a final voltage of 10.2 volts.
- c. **Cold Cranking Amps (CCA).** This rating defines the current available at -18° C for a period of 30 seconds, while being able to maintain a cell voltage exceeding 1.2 volts per cell. This rating is only applicable for engine starting purposes. The higher the rating the more power available, especially in cold weather conditions.
- d. **Plate Numbers.** Data sheets state the number of plates. This is defined as the number of positive and negative plates within a cell. The more plates, the greater the plate material surface area. This increases the current during high current rate discharges and subsequently cranking capacity and cold weather performance are improved.
- e. **Casing Type.** Battery casings are either a rubber compound or plastic. Where possible always select the rubber types if available, as they are more resilient to knocks and vibration.
- f. **Marine Battery.** This often misused sales term applies to certain constructional features. Plates may be thicker than normal or there may be more of them. Internal plate supports are also used for vibration absorption. Cases may be manufactured with a resilient rubber compound and have carry handles fitted. Filling caps may be of an anti-spill design. These days, batteries are of a similar design with very little to distinguish between the automotive types except the label. Buyer beware when this type of battery is touted as the be all, end all by salesmen, generally you are paying a premium for a label.

1.8. Battery Selection. The foundation of a reliable and efficient power system is a correctly specified and rated battery. Batteries are required to supply two different load types:

- a. **Service Loads.** These loads draw current over extensive time periods. Equipment included in this category are lights, instruments, radios, radar and autopilots.
- b. **Starting Loads.** These loads require large current levels for relatively short time periods. Loads in this category include engine starter motors, engine pre-heating, anchor windlass, electric winches and invertors.

1.9. Service Loads. Service loads require a battery that can withstand cycles of long continuous discharge, and repeated recharging. This deep cycling requires the use of the suitably named deep cycle battery. The deep cycle battery has the following characteristics:

- a. **Construction.** The battery is typified by the use of thick, high density flat pasted plates, or a combination of flat and tubular. The plate materials may also contain small proportions of antimony to help stiffen them. Porous, insulating separators are used between the plates and a glass matting is also used to assist in retaining active material on the plates which may break away as plates expand and contract during charge and recharge cycles. If material accumulates at the cell base, a cell short circuit may occur, although this is less common in modern batteries. If material is lost the plates will have reduced capacity or insufficient active material to sustain the chemical reaction with resultant cell failure.
- b. **Cycling.** The number of available cycles varies between individual battery makes and models. Typically it is within the range of 800-1500 cycles of discharge to 50% of nominal capacity and **complete** recharging. Battery life is a function of the number of cycles and the depth of cycling. Batteries discharged to only 70% of capacity will last appreciably longer than those discharged to 40% of capacity. In practice you should plan your system so that discharge is limited to 50% of battery capacity. The typical life of batteries in cruising yachts where batteries are properly recharged and cycle capabilities maximised is around 5 years.
- c. **Sulphation.** Sulphation is the single greatest cause of battery failure.
 - (1) During discharge, the chemical reaction causes both plates to convert to lead sulphate. If recharging is not carried out promptly and that means within a couple of hours, not days, the lead sulphate starts to harden and crystallise. This is characterised by white crystals on the typically brown plates and is almost non-reversible. If a battery is only 80% charged, this does not mean that only 20% is sulphating, the entire plate material has not fully converted and subsequently sulphates.
 - (2) The immediate effect of sulphation is partial and permanent loss of capacity as the active materials are reduced. Electrolyte density also partially decreases as the chemical reaction during charging cannot be fully reversed. This sulphated material introduces higher resistances within the cell and inhibits charging. As the level of sulphated material increases, the cell's ability to retain a charge is reduced and the battery fails. The deep cycle battery has unfairly gained a bad reputation, but the battery is not the cause, improper and inadequate charging is. As long as some charging is taking place, even from a small solar panel, a chemical reaction is taking place and sulphation will not occur.

- d. **Efficiency.** Battery efficiency is affected by temperature. At 0° C, efficiency falls by 60%. Batteries in warm tropical climates are more efficient, but may have reduced life-spans, and batteries commissioned in tropical areas often have lower acid densities. Batteries in cold climates have increased operating lives, but are less efficient.
- e. **Self Discharge.** During charging, a small quantity of antimony or other impurities dissolve out of the positive plates and deposit on the negative ones. Other impurities are introduced with impure topping up water and also deposit on the plates. A localised chemical reaction then takes place, slowly discharging the cell. Self discharge rates are affected by temperature, with the following results:
- (1) At 0° C, discharge rates are minimal.
 - (2) At 30° C, self discharge rates are high and the specific gravity can decrease by as much as 0.002 per day, typically up to 4% per month.
 - (3) The use of a small solar panel, or regular and **complete** recharging will prevent permanent damage as it can equal or exceed the self discharge rate.

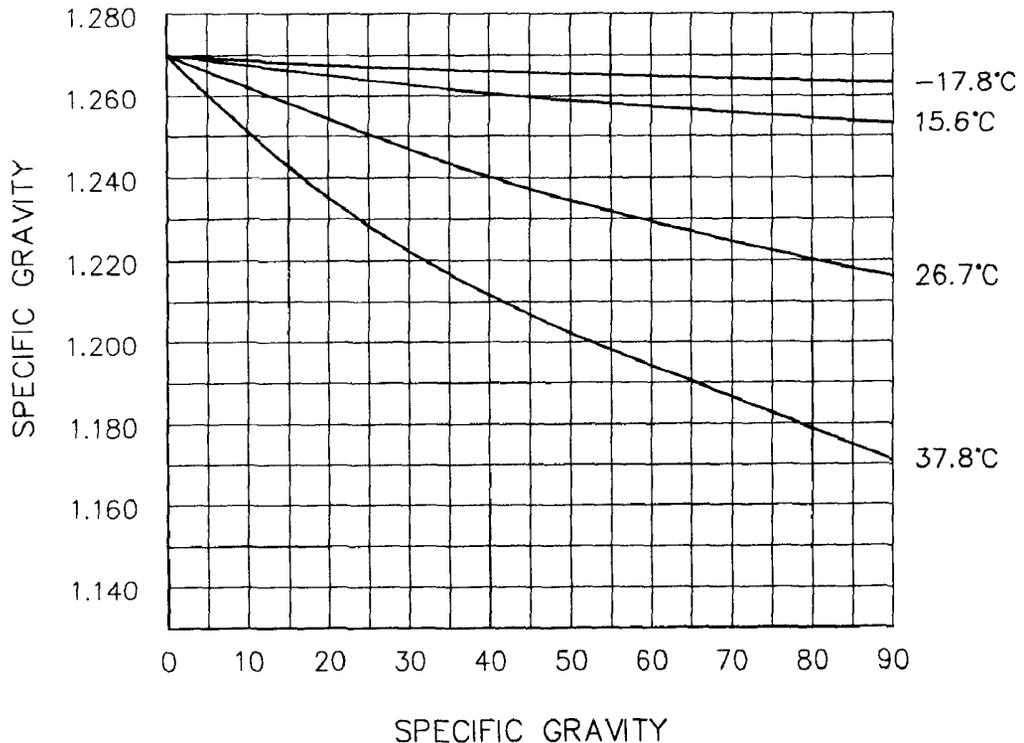


Figure 1-3. Self Discharge Rates.

f. Charging. Recommended charging rates for deep cycle batteries is often given as 15% of capacity. In vessel operations it is not possible to apply these criteria accurately. Essentially the correct charge voltage corrected for temperature should be used. Charging deep cycle batteries has the following characteristics:

- (1) During charging a phenomena called "counter voltage" occurs. Primarily this is caused by the inability of the electrolyte to percolate at a sufficiently high rate into the plate material pores and subsequently convert both plate material and electrolyte. This causes the plate surface voltage to rise, the battery resists charging and "fools" the regulator by showing an artificially high voltage with the recognisable premature reduction in charging.
- (2) To properly charge a deep cycle battery a charge voltage of around 14.5 volts is required, corrected for temperature. Contrary to some amazing assertions and statements in some marine electrical books, a charge level of approximately 80% does not represent a fully charged battery, and is not acceptable if you want a reliable electrical power system, and reasonable battery life. If you do not fully recharge the battery it will rapidly deteriorate and sustain permanent damage.

g. Equalisation Charge. An equalisation charge consists of applying a higher voltage level at a current rate of 5% of battery capacity. This is done to "re-activate" the plates. There is a mistaken belief that this will also completely reverse the effects of sulphation. There may be an improvement following the process, but it will not reverse long term permanent damage. Equalisation at regular intervals can increase battery longevity by ensuring complete chemical conversion of plates, but care must be taken.

- A: 10 HOUR DISCHARGE
- B: RAPID DISCHARGE
- C: CHARGING

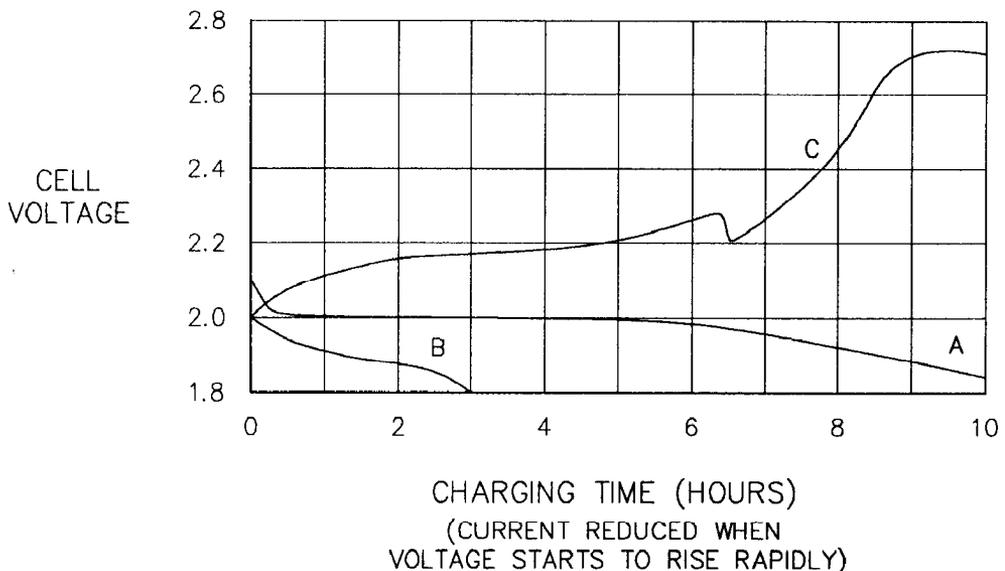


Figure 1-4. Lead Acid Battery Characteristics.

1.10. Starting Loads. The starting battery must be capable of delivering the auxiliary engine starter motor with sufficient current to turn and start the engine. This starting load can be affected by engine compression, oil viscosity, and engine driven loads. Some loads such as an inverter or an anchor windlass under full load require similar high values of current. Starting batteries have the following characteristics:

- a. **Construction.** The starting battery is characterised by thin, closely spaced porous plates which give maximum exposure of active plate material to the electrolyte and offer minimal internal resistance. This enables maximum chemical reaction rates, and maximum current availability. Physical construction is much the same as deep cycle batteries.
- b. **Cycling.** Starting batteries can not withstand cycling, and if deep cycled or flattened have an extremely short service life. Ideally they should be maintained within 95% of full charge.
- c. **Sulphation.** In practice, sulphation is not normally a problem, as batteries are generally fully charged if used for starting applications only. If improperly used for deep cycle applications they will sulphate.
- d. **Self Discharge.** Starting batteries have low self discharge rates and this is generally not a problem in normal engine installations.
- e. **Efficiency.** Cold temperatures dramatically affect battery performance. Engine lubricating oil viscosities are also affected by low temperatures, and further increase the starting loads on the battery. If the reduction in battery capacity in low temperatures is combined with the increased starting current requirements, the importance of fully charged batteries is amplified. Table 1-2 illustrates the typical cranking power loss when temperature decreases from 27° C to 0° C using a typical 10W-30 multi-viscosity lubricating oil and the increased percentage of power required to turn over and start an engine.

Table 1-2. Battery Power Table.

Temperature	Battery Level	Power Required
+ 27°C	100%	100%
0°C	65%	155%
- 18°C	40%	210%

f. **Charging.** Recharging of starting batteries is the same as for deep cycle batteries. There are a number of additional factors:

- (1) Discharged current must be restored quickly to avoid damage. Similarly temperature compensation must be made.
- (2) Normally after a high current discharge of relatively short duration, there is no appreciable decrease in electrolyte density. The battery is quickly recharged as the counter voltage phenomena does not have time to build up and therefore has negligible affect on the charging.

g. **Battery Ratings.** Starting batteries are normally specified on the basis of engine manufacturers recommendations, although I have found these to be vague and the following is given as a guide only. Table 1-3 shows recommended battery ratings and typical plate numbers for various diesel ratings as well typical starter motor currents:

- (1) **Start Capability.** It is practical to calculate a good safety margin allowing for a multi-start capability. Some classification societies specify a minimum of 6 consecutive starts, and this is a good practical guide to abide by.
- (2) **Temperature Allowance.** Additional allowances should be made for the decreased efficiency in cold climates as a greater capacity and greater load current is required.

h. **Additional Start Battery Loadings.** The start battery should also be used to supply short duration, high current loads. Check with your engine supplier for the recommended battery rating, and then add a margin or safety. Also factor in the following:

- (1) **Windlass.** Normally the recommended engine battery rating will suffice.
- (2) **Electric Winches.** The very heavy current loadings that electric winches requires a much higher bank rating. I would recommend simply doubling the battery bank, so two identical batteries are in parallel.
- (3) **Generator.** In some cases the engine battery can be used for starting. Be careful if starting the engine whilst it is running as the small 10 to 15 amp alternators regularly suffer damage from the engine load.

Table 1-3. Battery Ratings Table.

Engine Rating	Current Load	Battery CCA	Plates
10 Hp 7.5 kW	59 Amps	375 CCA	9
15 Hp 11 kW	67 Amps	420 CCA	11
20 Hp 15 kW	67 Amps	420 CCA	11
30 Hp 22 kW	75 Amps	450 CCA	13
40 Hp 30 kW	85 Amps	500 CCA	13
50 Hp 37 kW	115 Amps	500 CCA	13

1.11. Battery Rating Selection. This chapter covers the important task of selecting suitable batteries for use in service (housepower) roles. The majority of problems arise from improper battery selection. Battery bank capacities are either seriously under-rated with resultant power shortages, or over-rated so that the charging system cannot properly recharge them resulting in premature failure of the batteries due to sulphation. Initially, it is essential that all equipment on board is listed along with power consumption ratings. Ratings can usually be found on equipment nameplates or in equipment manuals. Normally I recommend that ratings, usually expressed in watts, are converted to current in amps. To do this simply divide the power by your system voltage. Calculate the current consumption for 12, 24 and 36 hours, at sea, in port, day and night periods. Table 1-4 illustrates typical power consumption, with space for you to insert and calculate your own vessel data. Base your calculations as follows:

- a. **Load Calculation Table.** To calculate the total system loading, multiply the total current values by the number of hours to get the amp-hour rating. If equipment uses 1 amp over 12 hours, then it consumes 12 Amp-hours.
- b. **Capacity Calculation.** Depending on the frequency between charging periods select the column that suits your vessel activity. The most typical scenario is one of operating the engine every 12 hours to pull down frig temperatures with an engine driven eutectic refrigeration compressor. A 24 hour rating may give a greater safety margin. If your port usage figure is larger, then select that as the worst case scenario.

Eg. Total consumption is 120 Ah over 12 hours = 10 amps per hour.

- c. **Capacity Derating.** As we wish to keep our discharge capacity to 50% of nominal battery capacity we can assume that a battery capacity of 240 Amp-hours is the basic minimum level. In an ideal world this would be a minimum requirement, but certain frightening realities must now be introduced into the equation. The figures below typify a common system, with alternator charging and standard regulator. Maximum charge deficiency is based on the premise that yacht batteries are rarely above 70% charge and cannot be fully recharged with normal regulators, and there is reduced capacity due to sulphation which is typically a minimum of 10% of capacity. The key to maintaining optimum power levels and avoiding this common and frightening set of numbers is the charging system, and this is covered extensively in Chapter 2.0.

Nominal Capacity		240 Ah
Maximum Cycling Level (50%)	Deduct	120 Ah
Maximum Charge Deficiency (30%)	Deduct	72 Ah
Lost Capacity (10%)	Deduct	24 Ah
Available Battery Capacity		24 Ah

d. **Amp-hour Capacity.** It is important to discuss a few more relevant points regarding amp-hour capacity as it has significant ramifications in selection of capacity and discharge characteristics.

(1) **Fast Discharge.** The faster a battery is discharged over the nominal rating (either 10 or 20 hour rate) the less the real amp-hour capacity there is. If we discharge our 240 amp-hour battery bank which has nominal battery discharge rates for each identical battery of 12 amps per hour at a rate of 16 amps we will actually have approximately 10-15% less capacity.

(2) **Slow Discharge.** Conversely the slower the discharge over the nominal rate the greater the real capacity. If we discharge our 240 amp-hour battery bank at 6 amps per hour we will actually have approximately 10-15% more capacity. The disadvantage here is that slowly discharged batteries are harder to charge if deep cycled below 50%.

e. **Battery Load Matching.** Ideally, the principal aim is to match the discharge characteristics of the battery bank to that of our calculated load of 10 amps per hour over 12 hours. Assume that we have a modified charging system so that we can recharge batteries to virtually 100% of nominal capacity. The factors affecting matching are as follows:

(1) **Discharge Requirement.** The nominal required battery capacity of 240 Ah has been calculated as that required to supply 10 amps per hour over 12 hours to 50% of battery capacity. In most cases the discharge requirements are worst for the night period, and this is the 12 hour period that should be used in calculations. What is required is a battery bank with similar discharge rates as the current consumption rate.

(2) **Battery Requirements.** As the consumption rate is based on a 12 hour period a battery bank which is similarly rated at the 10 hour rate is required. In practice you will not match the precise required capacity, therefore you should go to the next battery size up. This is important also as the battery will be discharged longer and faster over 12 hours, so a margin is required. If you choose a battery that has 240 amp-hours at the 20 hour rate in effect you will actually be installing a battery that in the calculated service has 10-15% less capacity than that stated on the label, which will then be approximately 215 Ah, so you are below capacity. This is not the fault of the supplier, but simply failing to calculate and buy the right battery for the job.

f. **Battery Capacity Formulas.** There are a range of formulas frequently put forward as a basis for selection of battery capacity. These are as follows:

- (1) **Four Day Consumption Formula.** One of the more unrealistic is that which states that you should be able to supply all the electrical needs over four complete 24 hour periods without charging. Given that an average 10 amps per hour is typical consumption that equates to 960 amp-hours. If we only require discharge to 50% that is an incredible 2000 amp-hour battery capacity. Additional to that is the recharging period, which requires an additional 20%, so around 1200 amp-hours must be replaced. With a fast charge device and a 100 amp alternator, and given that a battery has a finite charge acceptance rate you will need at least 12 hours charging.
- (2) **75/400 System.** This was included in a magazine article as one of three formulas for various sized vessels and was for a 40 to 45 foot yacht. This was the nearest I have seen to a rational set of numbers, based on a 75 amp consumption over 24 hours which is perhaps too conservative, and the formula is based on a 130-150 amp alternator with fast charge device to recharge half of a 400 amp-hour battery bank.
- (3) **Personal Formula (240/460 System).** My own personal formula is based on the worst case consumption of 240 amp-hours over 24 hours which entails the installation of two banks of 230 hour batteries, each battery bank made up from two 6 volt batteries. The batteries each supply a split switchboard, with electronics off one bank, with pumps and other circuits off the other limiting any interference. Charging is from an 80 amp alternator with a TWC cycle regulator through a diode isolator. Simple, and able to cope with all load conditions. Charging is relatively fast, and at a similar rate as the batteries ability to accept it.

1.12. Sailing Load Calculations. It is essential that all equipment on board is listed along with power consumption ratings. Ratings can usually be found on equipment nameplates or in equipment manuals. Normally I recommend that ratings, usually expressed in watts, are converted to current in amps. To do this simply divide the power by your system voltage. The two tables unlike normal consumption tables are broken down into the different load consumption scenarios. Spaces are provided to insert and calculate your own specific vessel loads.

- a. **Sailing Modes.** Add up all the current figures relevant to your vessel and multiply by hours to get an average amp-hour consumption rate for each sailing mode. Space is reserved to add in any specific equipment you may have.
- b. **Cumulative Load.** Add both day and night figures together to get the average current drain on your batteries over the selected period.

Table 1-4 (a). DC Load Calculation Table.

Equipment	Typical	Actual	12 Hrs	24 Hrs
Day Sailing				
Radar-Stby	2.0 A	_____	_____	_____
AutoPilot	6.0 A	_____	_____	_____
SSB-Receive	1.0 A	_____	_____	_____
VHF-Receive	0.5 A	_____	_____	_____
CB-Receive	0.5 A	_____	_____	_____
Cabin Htr	2.0 A	_____	_____	_____
Weatherfax	1.0 A	_____	_____	_____
Electric Frig	4.0 A	_____	_____	_____
GPS/Satnav	1.0 A	_____	_____	_____
LORAN	1.0 A	_____	_____	_____
Instruments	1.0 A	_____	_____	_____
Stereo/CD	1.0 A	_____	_____	_____
Gas Detect	0.3 A	_____	_____	_____
Invertor Stby	0.5 A	_____	_____	_____
Switchbd Lts	0.3 A	_____	_____	_____
		_____	_____	_____
		_____	_____	_____
Load Sub Total		_____	_____	_____
Night Sailing				
Radar-On	3.5 A	_____	_____	_____
Tricolour	1.0 A	_____	_____	_____
Chart Lt	0.5 A	_____	_____	_____
Compass Lt	0.2 A	_____	_____	_____
GPS Lt	0.5 A	_____	_____	_____
LORAN Lt	0.5 A	_____	_____	_____
Bunk Light	1.0 A	_____	_____	_____
Instr. Lights	0.5 A	_____	_____	_____
Red Night Lt	0.5 A	_____	_____	_____
		_____	_____	_____
Load Sub Total		_____	_____	_____
Sailing Total		_____	_____	_____

1.13. Additional Load Calculations. There are other basic load characteristics that have to be factored in to load calculations. Add up all the current figures relevant to your vessel and multiply by expected times to get an average amp-hour consumption rate.

- a. **Intermittent Loads.** It is often hard to quantify actual real current demands with intermittent loads. My suggestion is simply to use a baseline of 6 minutes per hour which is .1 of an hour. It must be remembered that start up loads have to be factored into these figures so this is a realistic average.
- b. **Anchorage/Port Loads.** Port or anchorage loads vary greatly and you will have to carefully assess your own load characteristics.
- c. **Motoring Loads.** It is often forgotten, but certain loads are also added when motoring, and these are in addition to any combination of listed values. Loads must be subtracted from charge values.

Table 1-4 (b). DC Load Calculation Table.

Equipment	Typical	Actual	12 Hrs	24 Hrs
Intermittent Loads				
Bilge Pump	4.0 A	_____	_____	_____
Shower Pp	6.0 A	_____	_____	_____
FW Pump	4.0 A	_____	_____	_____
SW Pump	2.5 A	_____	_____	_____
Toilet	18.0 A	_____	_____	_____
Macerator	15.0 A	_____	_____	_____
SSB-Xmit	15.0 A	_____	_____	_____
VHF-Xmit	4.0 A	_____	_____	_____
F/deck Spot	3.0 A	_____	_____	_____
Extract. Fan	1.0 A	_____	_____	_____
Invertor	40 A	_____	_____	_____
Cabin Lts	1.5 A	_____	_____	_____
Load Sub Total		_____	_____	_____
Anchorage/Port Loads				
Anchor Lt	1.0 A	_____	_____	_____
Spreader Lt	4.0 A	_____	_____	_____
Cockpit Lt	1.5 A	_____	_____	_____
Cabin Lt	1.5 A	_____	_____	_____
Bunk Lt	1.5 A	_____	_____	_____
Cabin Fan	1.0 A	_____	_____	_____
Wash Pp	6.0 A	_____	_____	_____
Load Sub Total		_____	_____	_____
Motoring Loads				
Bicolour	1.0 A	_____	_____	_____
Stern	1.0 A	_____	_____	_____
Steaming	1.0 A	_____	_____	_____
Frig Clutch	5.0 A	_____	_____	_____
Desalinator	5.0 A	_____	_____	_____
Vent. Fan	4.0 A	_____	_____	_____
Load Sub Total		_____	_____	_____
LOAD TOTAL		_____	_____	_____

1.14. Battery Installation. Batteries must be installed correctly, and there are a number of important criteria to consider when installing battery banks to make up required voltage and capacity:

a. **Cell Size.** Battery banks may be installed either in cell multiples of 1.2 volts, 6 volts, or 12 volts. Each configuration has advantages both physically and operationally:

- (1) **1.2 Volt.** This is generally impractical from an overall size aspect. The battery plates are generally more robust and thicker. This leads to increased service life, but it is an expensive option.
- (2) **6 Volt.** This is the ideal arrangement. The cells are far more manageable to install and remove. Large capacity batteries are simply connected in series. Electrically they are better than 12 volt batteries, generally having thicker and more durable plates. Contrary to some opinions, a series arrangement does not necessarily reduce the available power range, nor does it require an equalisation network, and these are rarely found. The one proviso is that batteries must be of the same make, model and age. Replace one, then replace both.
- (3) **12 Volt.** This is the most common arrangement. Physically batteries up to around 105 Ah are easily managed, and paralleled in banks of up to 3 is the most common arrangement. It is not uncommon to see traction or truck batteries of very large dimensions installed and this is totally impractical from any service stand-point. If the battery space is constructed to take a 3 battery arrangement it is relatively easy to replace one unit. Additionally if you have a multiple bank and lose one with cell failure, you still have two.
- (4) **24 Volt.** This is simply any of the above battery or cell sizes connected in series to get the 24 volts.

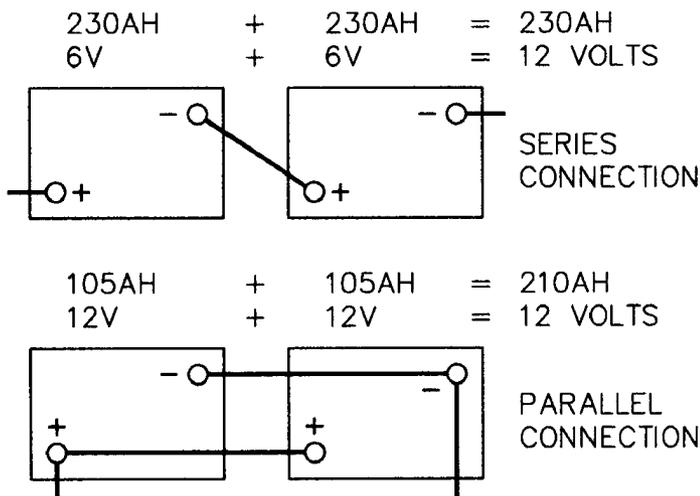


Figure 1-5. Cell and Battery Arrangements.

- b. **Battery Housing.** The batteries should be installed in a lined box protected from temperature extremes. The preferred temperature range is 10°C - 27°C. The box should be made of plastic, fibreglass or lead lined to prevent any acid spillage's contacting with wood or water. The box should be located as low down as possible in the vessel for weight reasons, but high to avoid bilge water or flooding.
- c. **Battery Ventilation.** The area should be well ventilated and vented to atmosphere. The use of an extraction fan is rarely required. I have started to use solar powered vent fans with integral battery for round the clock positive ventilation with great success. The larger the battery bank, the more ventilation required. If you install any fast charging device, ensure that the ventilation is satisfactory or improved.
- d. **Battery Lighting.** Sufficient natural light should be available for testing or servicing. If this is not possible a vapour proof light can be installed.
- e. **Battery Access.** Allow sufficient clearance to install and remove batteries. Ensure there is sufficient vertical clearance to allow hydrometer testing.
- f. **Battery Electrical Equipment.** Do not install electrical equipment adjacent to batteries if at all possible, as sparks may be accidentally generated and cause ignition of hydrogen gas, particularly after charging.
- g. **Battery Orientation.** The ideal configuration is an athwartships arrangement. This offers a marginally better protection against acid spilling under excess heeling. Even in a fore and aft layout I have not come across any adverse problems. I have even seen a gimballed tray on a friends steel cruising yacht, "Xarifa", to prevent spillage's, although this is an impractical and unnecessary innovation.
- h. **Battery Security.** Physically secure batteries with either straps or a removable restraining rod across the top. Batteries must not be able to move around. Insert rubber spacers around the batteries to stop any minor movements and vibrations.
- i. **Battery Location.** The location of the batteries is extremely important. Ideally batteries should not be located within machinery spaces to avoid excessive ambient temperatures. There are considerations for vessel types:
 - (1) **Monohulls.** Battery boxes or compartments should be mounted clear of areas liable to flood. After a bad knockdown, and with water over the sole, many boats have compounded their problems by having the batteries contaminated with salt-water.
 - (2) **Multihulls.** With trimarans, battery locations are the same as monohulls. Catamaran batteries should either be located centrally in the mast area, or have two banks split with one in each hull, effectively giving two separate house banks, plus the two engine start batteries.

1.15. Battery Commissioning. After installation the following commissioning procedures should be carried out:

- a. **Battery Electrolyte Level.** Check the electrolyte level in each cell as follows:
 - (1) Cells with separator guard - fill to top of guard.
 - (2) Cells without guard - fill to 2mm above plates.
- b. **Battery Electrolyte Filling.** If the level is low, and evidence suggests a loss of acid in transit, refill with an electrolyte of similar density. Specific Gravity is normally in the range 1.240 to 1.280 at 15° C. If no evidence of spillage is apparent, top up electrolyte levels with de-ionised or distilled water to the correct levels.
- c. **Battery Terminals.** Battery terminals are a simple piece of equipment, yet they cause an inordinate amount of problems:
 - (1) **Terminals.** Install heavy duty marine grade brass terminals. Do not use the cheaper plated brass terminals, as they are not robust and fail quickly. Don't use the snap on quick release terminals or those with integral security switch. These tend to fail prematurely at the worst possible time, as resistance is introduced into the circuit causing voltage drops, and a hot spot often occurs under high current conditions.
 - (2) **Clean Terminals.** Ensure that terminal posts are clean. Ensure that they do not have any raised sections, and are not deformed, as a poor connection will result.
 - (3) **Replace Connections.** Replace the standard wing-nuts on terminals with stainless steel nuts and washers. The wing-nuts are very difficult to tighten properly without deformation and breakage. I have encountered many installations where the wings are broken, and the casting broken.
 - (4) **Coat Terminals.** Coat the terminals with petroleum jelly.
- d. **Battery Cleaning.** Cleaning involves the following tasks:
 - (1) **Clean Surfaces.** Clean the battery surfaces with a clean, damp cloth. Moisture and other surface contaminations can cause surface leakage between the positive and negative terminals.
 - (2) **Grease and Oil Removal.** Grease and oil can be removed with a mild detergent and cloth.
- e. **Battery Charging.** After taking delivery of a new battery perform the following:
 - (1) **Initial Charge.** Give a freshening charge immediately.
 - (2) **Routine Charging.** Give a charge every week if the vessel is incomplete or not in service.

1.16. Battery Routine Testing. The following tests can be made on a daily and weekly basis to monitor the condition of the battery. Battery status can be measured by checking the electrolyte density and the voltage as follows:

- a. Stabilised Voltage Test.** Voltage readings should be taken with an accurate voltmeter. Switchboards should incorporate a high quality meter, not a typical engine gauge charge indicator. The difference between fully charged and discharged is less than 1 volt, so accuracy is essential. A digital voltmeter is the ideal. Battery voltage readings should only be taken a minimum of 30 minutes after charging or discharging. Turn off all loads before measuring. Typical values at 15 °C are shown in Table 1-5. Manufacturers have slightly varying densities so check with your supplier.

Table 1-5. Typical Open Circuit Voltages & Densities.

Charge Level	SG Temperate	SG Tropical	Voltage
100%	1.250	1.240	12.75
90%	1.235	1.225	12.65
80%	1.220	1.210	12.55
70%	1.205	1.195	12.45
60%	1.190	1.180	12.35
50%	1.175	1.165	12.25
40%	1.160	1.150	12.10
30%	1.145	1.135	11.95
20%	1.130	1.120	11.85
10%	1.115	1.105	11.75
0%	1.100	1.090	11.65

- b. Battery Electrolyte Specific Gravity.** A hydrometer should be used weekly to check acid density. The hydrometer is essentially a large syringe with a calibrated float. The calibration scale is corrected to a nominal temperature value, which is normally marked on the float. The following points should be observed during testing with a hydrometer:

- (1) Never test immediately after charging or discharging. Wait at least half an hour until the cells stabilise, this is because it takes some time for the pockets of varying electrolyte densities to equalise.
- (2) Never test immediately after topping up the electrolyte. Wait until after a charging period, as it similarly takes times to for the water to mix evenly.
- (3) Ensure the float is clean and not cracked and the rubber has not perished.
- (4) Keep the hydrometer completely vertical. Ensure that the float does not contact the side of the barrel, which may give a false reading.
- (5) Draw sufficient electrolyte into the barrel to raise the float. Ensure that the top of the float does not touch the top.

(6) Observe the level on the scale. Disregard the liquid curvature caused by surface tension. Adjust your reading for temperature to obtain the actual value.

(7) Wash out the hydrometer with clean water.

c. **Battery Load Test.** The load test is carried out only if the batteries are suspect. The load tester consists of two probes connected by a resistance and a meter. The tester is connected across the battery terminals effectively putting a heavy load across it. The load is typically 275 amps at 8 volts. Take your suspect battery to your nearest automotive electrician or battery service centre for a test.

1.17. Battery Maintenance. Battery maintenance is simple and is not the tedious chore that it is often made out to be. The following tasks should be carried out:

a. **Battery Terminal Cleaning.** (Bi-monthly). Remove battery terminals and ensure that terminal posts are clean and free of deposits. Refit and tighten terminals and coat with petroleum jelly, not grease.

b. **Battery Electrolyte Checks.** (Monthly). Check levels along with density. Record each cell density so that a profile can be built up. Record the battery voltage as well. Top up cells as required with distilled or de-ionised water.

c. **Battery Cleaning.** (Monthly). Wipe battery casing top clean with a damp rag. Moisture and salt can allow tracking across the top to ground or negative, slowly discharging the battery. A common cause of flat batteries, and the mysterious but untraceable system "leak".

Table 1-6. Lead-Acid Battery Fault Finding.

Symptom	Probable Fault
Will Not Accept Charge. Low Cell Electrolyte SG Battery Low SG Level	Plates sulphated Cell plate sulphated Low charge level
Will Not Support Load	Plates sulphated Low charge level Sulphated plates
Cell Failure	Improperly commissioned Electrolyte contamination Overcharging Undercharging Excessive vibration Cell internal short circuit
Battery Warm When Charging	Sulphated plates High charge current Cell damage

1.18. Low Maintenance Batteries. Sealed low maintenance batteries are not suited to cruising vessel applications. Frequently they are installed without considering their performance characteristics or the various advantages and disadvantages:

- a. **Low Maintenance Principles.** Basic chemical reactions are similar to the conventional lead-acid cell and the differences are as follows:
 - (1) **Lead Acid Batteries.** In a normal lead-acid battery water loss occurs when it is electrically broken down into oxygen and hydrogen close to the end of charging. In a any battery during charging, oxygen will evolve at the positive plate at approximately 75% of full charge level. Hydrogen evolves at the negative plate at approximately 90% of full charge. In normal batteries, the evolved gases disperse to atmosphere, resulting in electrolyte loss and periodic water replacement. These are the bubbles seen in the cells during charging.
 - (2) **Low Maintenance Batteries.** The low maintenance recombinational battery has different characteristics. The plates and separators are held under pressure. During charging, the evolved oxygen is only able to move through the separator pores from positive to negative, reacting with the lead plate. The negative plate charge is then effectively maintained below 90% so inhibiting hydrogen generation.
- b. **Low Maintenance Battery Safety.** Batteries are totally sealed, but incorporate a safety valve. Each cell is also sealed, with a one way vent. When charging commences, oxygen generation exceeds the recombination rate and the vents release excess pressure within the battery. Excess charge rates create internal pressure build-up and if the internal safety vent discharge rate is exceeded, explosion can occur.
- c. **Charging.** Low maintenance batteries must only be charged at recommended charging rates and charge starting currents. The result of any overcharging may be explosion.
- d. **Advantages.** The following are advantages of low maintenance batteries:
 - (1) **Low Water Loss.** Low water loss is the principal advantage, however performing a routine monthly inspection and occasional topping up of a lead acid battery is not so labour intensive or inconvenient. I am amazed that this factor is the main one put forward as the criteria for these batteries. If you are continually topping up, then you have a charging problem or a high ambient temperature.
 - (2) **Inversion, Heel and Self Discharge.** The batteries are safe at inversion or excessive heel angles without acid spilling, and have a low self discharge rate.

c. **Disadvantages.** There are two major disadvantages that make low maintenance batteries unsuitable for cruising applications:

- (1) **Over Voltage Charging.** Low maintenance batteries are incapable of withstanding any over-voltage during charging. If they are subjected to high charging voltages (above 13.8 V), water will vent out and they have been known to explode. This means no fast charging devices should be installed to charge them.
- (2) **Cycle Availability.** Cycle availability is restricted, and an approximate life-span of 500 cycles to 50% of nominal capacity is typical. Any discharge to 40% of capacity or less makes recharging extremely difficult if not impossible, and requires special charging techniques.

1.19. Gel Cell Batteries. These battery types are known as Dryfit or Prevailer batteries. The principal characteristics are as follows:

- a. **Electrolyte.** Unlike normal lead-acid cells they have a thixotropic gel as an electrolyte which is locked into each group of plates. Thixotropic gels have a reduced viscosity under stress. Sonnenschein are the major manufacturer of these batteries and have advanced the chemical technology of these types by the use of phosphoric acid to retard the sulphation hardening rates.
- b. **Construction.** The batteries have plates that are reinforced with calcium, rather than antimony, which reduces self discharge rates. The plates are relatively thin, which facilitates gel diffusion into them, and does make charge acceptance easier, as diffusion problems are reduced.
- c. **Charging.** Charging of Gel cells have a number of important factors as follows:
 - (1) **Over Voltage Intolerance.** Gel cells are unfortunately intolerant to over voltage charge conditions and will be seriously damaged in any over charge situation. The normal optimum voltage tolerance for these battery types is 13.8 volts, 14.2 volts being the absolute maximum.
 - (2) **Charge Acceptance.** A Gel cell has a much higher charge acceptance rate, and therefore a more rapid charge rate is possible. A Gel cell cannot tolerate having any equalising charge applied and this over charge condition will seriously damage them.
 - (3) **Fast Charging.** Although accepting a higher charge rate than a lead-acid deep cycle battery, and consequentially charging to a higher value, there is at a certain point the problem of attaining full charge, and therefore capacity usage of the battery bank. As no fast charge devices can be used, a longer engine run time is required for complete recharging.

- d. **Selection Criteria.** With respect to very good battery technology, these batteries are not suited to cruising yacht applications for the following reasons:
- (1) **Cycle Life.** A deep cycle lead acid battery can have a life exceeding 2500 cycles of charge and discharge to 50%. A gel cell has a life of approximately 800-1000 cycles. There are a few misconceptions on cycle life comparisons. They do have a much greater cycling capability than normal starting batteries, but not deep cycle batteries.
 - (2) **Costs.** It is difficult to justify a battery that initially costs up to 50% more, is more susceptible to problems encountered on the average yacht, lasts less than half the time of a conventional battery, and all that based on not spending five minutes a month checking electrolyte densities and levels.
 - (3) **Charging.** While these batteries will accept some 30-40% greater current than an equivalent lead acid battery they are restricted in the voltage levels allowed, so you cannot use any fast charging system.
- e. **Suitable Applications.** Gel cells are ideally suited to stand-by power applications where good charging facilities are installed. If you are a day or weekend sailor, that does little motoring, and leave the vessel unattended for extended periods, then the Gel cell is a viable proposition, as it has low self discharge rates, and less prone to the problems of deep cycle batteries. If a small solar panel is left on with a suitable regulator, they will recoup the annual costs of replacing deep cycle batteries by lasting a few seasons.

1.20. Nickel Cadmium Batteries. Nickel Cadmium batteries are not used extensively on vessels, but they should be considered. I have only worked on one installation with a charging or battery problem and that was on the beautiful Tasmanian built, and UK fitted out cruising vessel "Cascade". The principal factors are cost, (typically 500% greater), weight and size. Normally these batteries will only be found in larger cruising vessels for those reasons. They have completely different operating characteristics to the lead-acid cell:

- a. **Cell Components.** The components of the cell are:
 - (1) Nickel-Hydroxide ($2Ni(OH)_2$) - the positive plate.
 - (2) Cadmium Hydroxide ($Cd(OH)_2$) - the negative plate.
 - (3) Potassium Hydroxide (KOH) - the electrolyte.
- b. **Discharge Cycle.** Cells are usually characterised by their rate of discharge characteristics, such as low, medium, high or ultra high. Classification UHP is for starting applications and VP for general services. There is also a category for deep cycle applications. Discharge ratings are given at the five hour rate and typically they will deliver current some 30% longer than lead-acid equivalents. The amp-hour capacity rating remains fairly stable over a range of discharge currents values. An over-discharge condition can occur when the cell has been driven into a region where voltage has become negative. A complete polarity reversal takes place. No long term effects occur on occasional cell reversal at medium discharge rates.

Curve A - Discharge current reduces cell voltage from 1.3 volts to 1.0 volt over 10 hours.

Curve B - Discharge over three hours.

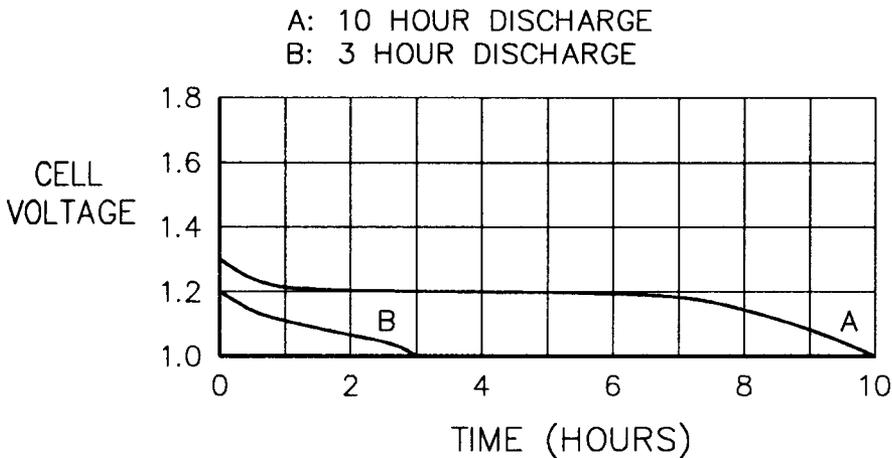


Figure 1-6. NiCad Battery Discharge Characteristics.

c. **Charge Cycle.** During charging, the negative material loses oxygen and converts to metallic cadmium. The positive material gradually increases in the state of oxidation. While charging continues, the process will proceed until complete conversion occurs. Approaching full charge gas will evolve and this results from electrolysis of the electrolyte water component. NiCad cells can be charged rapidly with a relatively low water consumption. The disadvantages are that cell imbalances may occur and this can cause thermal runaway. The NiCad cell will generally absorb maximum alternator current for about 85% of the cell charge period, so the alternator must be capable of withstanding this load and have adequate ventilation:

- (1) **Regulator Voltage Settings.** Typical alternator voltage regulator settings for a nominal 12 volt battery bank of 10 cells over a 2-4 hour period should be in the range of 15 to 15.5 volts maximum. A NiCad battery accepts high charge currents and will not be damaged by them. At 1.6 volts per cell a NiCad can absorb up to 400% of capacity from a charging source. In most cases it will accept whatever the alternator can supply. The problem with normal alternator regulators is that they fix the output at only 14 volts which is far too low for proper charging. Absolute maximum charging rates require a 1.6 to 1.8 volts per cell which is 16-18 volts on a typical 10 cell battery bank.
- (2) **NiCad Charging Controllers.** The typical 14 volt output of an alternator is a float charge voltage level only for a NiCad battery. An alternator controller is essential for correct charging, and the Solent Chagemaster ideally suits this application, enabling setting of the required level. I have set up this type of regulator with a CAV alternator successfully. Constant voltage charging is the only practical method of charging on vessels. Regulator setting should be typically around 15.5 volts for a 2-4 hour charge period, higher voltages will increase current.

Curve C - Charging cell voltage 1.5 times the 10 hour discharge current.

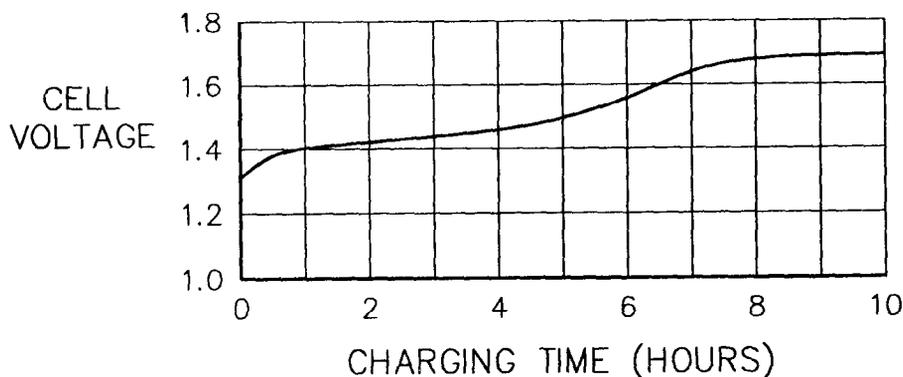


Figure 1-7. NiCad Battery Charge Characteristics.

1.21. NiCad Electrolyte. The obvious difference is the use of an alkaline electrolyte instead of an acid. Unlike lead-acid cells, plates undergo changes in their oxidation state, altering very little physically. As the active materials do not dissolve in the electrolyte, plate life is very long. The electrolyte is a potassium hydroxide solution with a specific gravity of 1.3. The electrolyte transports ions between the positive and negative plates and the alkaline solution is chemically more stable than lead-acid cell electrolytes. Unlike lead-acid cells the density does not significantly alter during charge and discharge and hydrometer readings cannot be used to determine the state of charge. Electrolyte loss is relatively low in operation. There are two basic factors to consider with NiCad cells:

- a. **Electrolyte Topping Up.** Water additions should be made immediately after charging, and never after discharging.
- b. **Mixed Battery Installations.** Lead-acid and NiCad batteries should never be located in the same compartment as the cells will become contaminated by acid fumes causing permanent damage.

1.22. NiCad Battery Characteristics. The NiCad has the following characteristics:

- a. **NiCad Open Circuit Voltage.** The typical open circuit voltage of a vented cell is 1.28 volts. This depends on temperature and time interval from last charge period. Unlike a lead-acid cell, the voltage does not indicate the state of charge.
- b. **NiCad Nominal Voltage.** Nominal voltage is typically 1.2 volts. This voltage is maintained during discharge until approximately 80% of the 2 hour rated capacity has been discharged. This is also affected by temperature and rate of discharge.
- c. **NiCad Closed Circuit Voltage.** This voltage is measured immediately after load connection. Typically it is around 1.25 - 1.28 volts per cell.
- d. **NiCad Working Voltage.** This voltage is that observed on the level section of the discharge curve of a NiCad cell, voltage plotted against time. Typically the voltage averages 1.22 volts per cell.
- e. **NiCad Capacity.** Capacity is specified in amp-hours. Normally it is quoted at the five hour rate.
- f. **NiCad Nominal Rating.** The nominal rating is the amp-hour delivery rate over 5 hours to a nominal voltage of 1.0 volt per cell.
- g. **NiCad Internal Resistance.** Internal resistance values are typically very low. This is due to the large plate surface areas used and is why the cells can deliver and accept high current values.

BATTERY CHARGING SYSTEMS

2.0. Charging Systems. An efficient charging system is essential for optimum battery and electrical system performance. I receive literally hundreds of letters and phone calls from boat owners who are totally confused by conflicting information and simply want a reliable system. The principal charging systems on cruising vessels consist of the following:

- a. **Alternators.** The principal charging source on all cruising yachts.
- b. **Alternative Energy Systems.** The following methods of auxiliary charging are available as options to augment engine charging sources:
 - (1) **Solar Panels.**
 - (2) **Wind Generators.**
 - (3) **Prop Shaft Alternators.**
 - (4) **Water Charging Systems.**
- c. **Mains Powered Battery Chargers.** The average cruising yacht does not normally spend long periods alongside. Where a vessel is alongside, and particularly in liveaboard situations where the main power source is via a shore powered charger the mains charger is an important charging source.

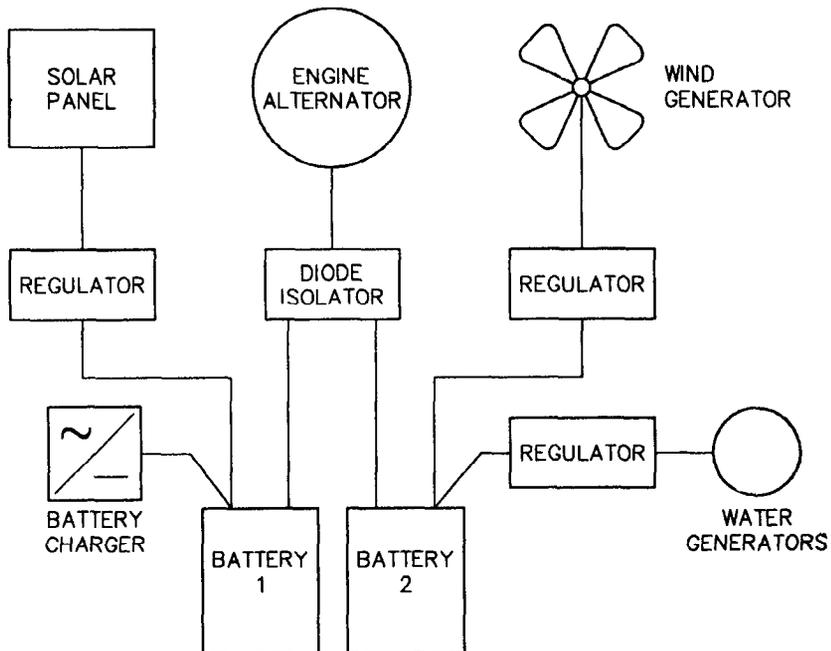


Figure 2-1. Charging Systems.

2.1. Charging Cycles. There are four recognised parts of any charging cycle, and these are as follows:

- a. **Bulk Charge.** The bulk charge phase is the initial charging period where charging takes place until the gassing point is reached, typically in the range 14.4 to 14.6 volts corrected for temperature. Obviously on a traditional alternator and regulator this does not relate as output is fixed at 14 volts. The bulk charge rate can be anywhere between 25% and 40% of rated amp-hour capacity at the 20 hour rate as long as temperature rises are limited.
- b. **Absorption Charge.** After attaining the gassing voltage, the charge level should be maintained at 14.4 volts until the charge current falls to 5% of battery capacity. This level normally should equate to 85% of capacity. In a typical 300 amp-hour bank, this will be 15 amps.
- c. **Float Charge.** The battery charge rate should be reduced to a float voltage of approximately 13.2 to 13.8 volts to maintain the battery at full charge.
- d. **Equalisation Charge.** A periodic charge should be applied which should be rated at 5% of the installed battery capacity for a period of 3-4 hours until a voltage of 16 volts is reached. A suitable and safer way of equalising is applying the unregulated output from the wind generator or solar panel once a month for a day.

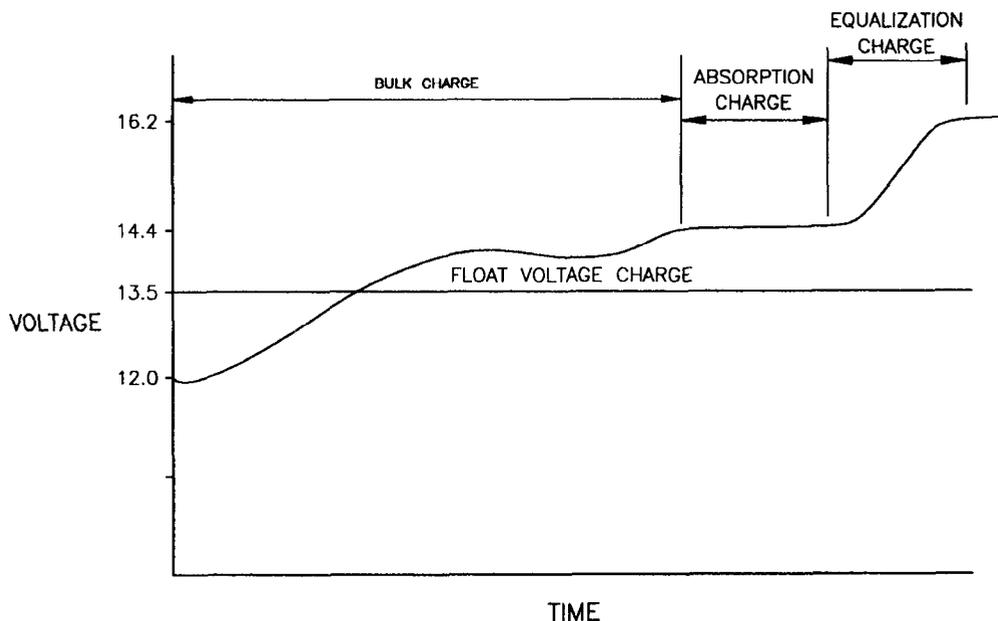


Figure 2-2. Charging Cycles.

2.2. Charging Efficiency. Before any charging systems can be considered, a number of factors must be remembered and taken into account as follows:

- a. **Battery Capacity.** Nominal capacities of batteries are specified by manufacturers, and the total capacity of the bank must be taken into consideration.
- b. **Battery Age and Condition.** Older batteries have reduced capacities due to normal in-service aging, and plate sulphation. Sulphation increases internal resistance and inhibits the charging process.
- c. **Electrolyte.** The electrolyte is temperature dependant, and the temperature is a factor in setting maximum charging voltages.
- d. **State of Charge.** The state of charge at charging commencement can be checked using the open circuit voltage test and electrolyte density. The level of charge will affect the charging rate. Also critical to the state of charge is the temperature. It has a dramatic effect on charge voltages as indicated in the curve below.

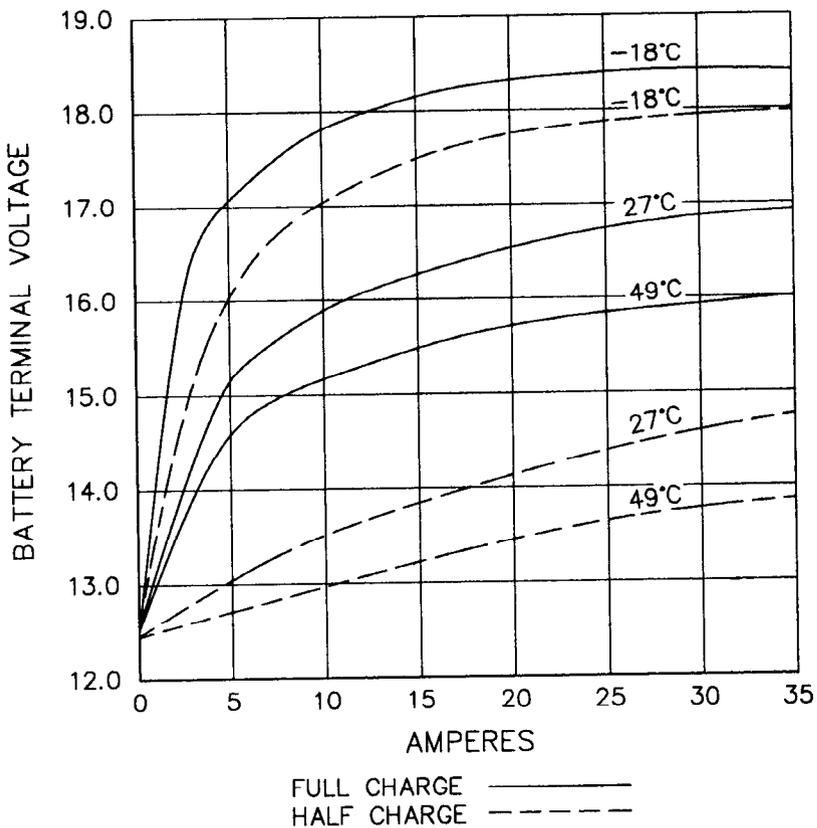


Figure 2-3. State of Charge/Temperature Characteristics.

e. **Charging Voltage.** Charging voltage is defined as the battery voltage plus the cell voltage drops. These are explained as follows:

- (1) **Cell Volt Drops.** Cell volt drops are due to internal resistance, plate sulphation, electrolyte impurities and gas bubble formation that occurs on the plates during charging. These resistances oppose the charging and must be exceeded to effectively recharge the battery. Resistance to charging increases as a fully charged state is reached and decreases with discharge.
- (2) **Charge Regulation.** A battery is self regulating in terms of the current it can accept under charge. Over-current charging at excessive voltages (which many so called fast charging devices do) simply generates heat and damages the plates which is why they are discouraged.

2.3. Alternator Charging. The alternator is the principal charging source on most marine installations. In the majority of installations it is incorrectly rated for the installed battery capacity, and therefore is unable to properly restore the discharged current. The alternator is a robust and reliable piece of equipment and automotive alternators, or derivatives of them are used in the majority of marine installations. These have a number of limitations which must be considered during installation. The illustration below has been reproduced of a Bosch alternator showing all the main components courtesy of Bosch (Australia).

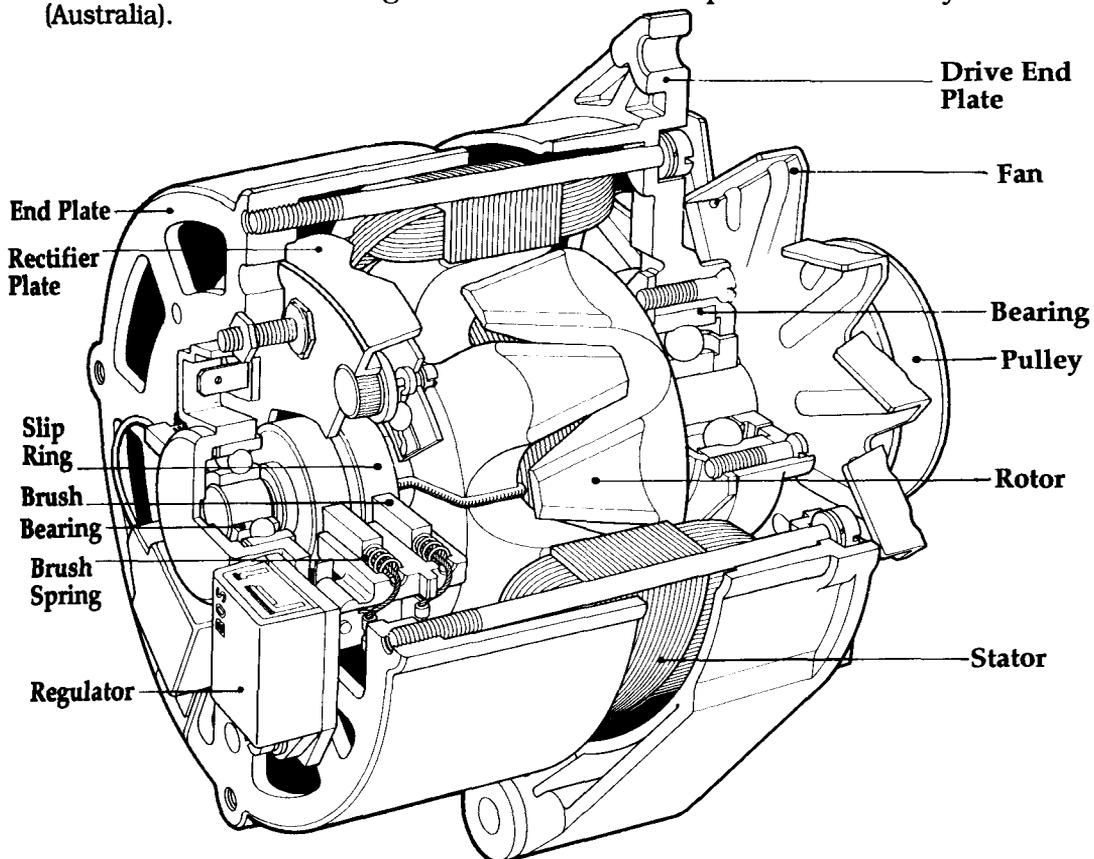


Figure 2-4. Bosch Alternator.

2.4. Alternator Components. The alternator consists of several principal physical components:

- a. **Stator.** The stator is the fixed winding. It consists of three windings that are interconnected in a "star" or a "delta" arrangement. These windings supply three phases of alternating current (AC) to the diode bridge.
- b. **Rotor.** The rotor is the rotating part of the alternator, and consists of the sliprings, and the winding, which are interconnected.
- c. **Rectifier.** The diode bridge consists of a network of six diodes. This rectifies the three AC phase voltages into the DC output used for charging. Two diodes are used on each winding to provide full wave rectification. The three DC voltages are connected in parallel to the main output terminal.
- d. **Exciter Diodes.** The exciter (D+) consists of three low power diodes which independently rectify each AC phase and provide a single DC output for the warning light or auxiliary control functions.
- e. **Brushgear.** The brushes are normally made of graphite, or on some high performance alternators copper graphite. The brushes are spring-loaded to maintain correct slip-ring contact pressure and are solder connected to the terminals.
- f. **Regulator.** The regulator, if integral to the alternator, is often combined with the brushgear or mounted adjacent to it. The field control output of the alternator is connected to one of the brush holders, which then supplies the rotor winding through the slipring. Regulator sensing is taken from the D+ connection.

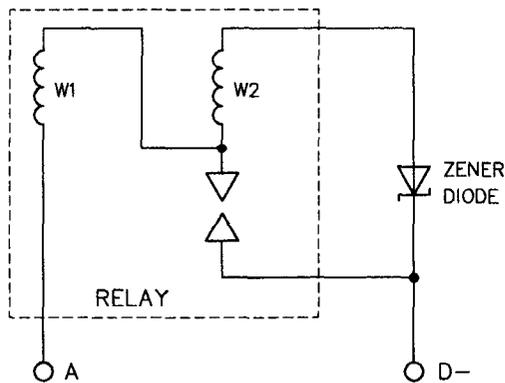
2.5. Alternator Selection. Yacht owners have a number of important factors to consider when selecting alternator output ratings. The alternator is probably the most common failure item on board, along with regulators, therefore careful selection is required. The factors are summarised as follows:

- a. **Engine Run Times.** The majority of cruising vessels run engines for excessive periods attempting to recharge batteries. The maximum run time goal is one hour in the morning and one hour in the evening, which coincides with refrigeration pull down times.
- b. **Engine Loading.** Diesel engines should not be run with light loads as unloaded engines suffer from cylinder glazing. A high output alternator can provide loads of up to 2 kW if at rated output.
- c. **Engine Speeds.** Ideally, the engine should be able to charge at maximum rates at relatively low speeds. The most preferred speed is a few hundred revs/min above idle speed. The alternator speed is dependent on the drive pulley ratio and the alternator cut-in speed.
- d. **Battery Capacity.** Nominal charging rates are specified by manufacturers and they generally specify starting and finishing rates. A battery requires the replacement of 120% of the discharged current to restore it to full charge. This value is required to overcome losses within the battery due to battery internal resistances during charging.

- e. Charging Current.** As a battery is effectively self limiting in terms of charge acceptance levels, we cannot simply push in the discharged value and hope that it will recharge. The battery during charging is reversing the chemical reaction of discharge, and this can only occur at a finite rate. The alternator therefore must be selected if possible to recharge at the battery optimum charge rate as specified. Charging by necessity has a tapered characteristic, which is why start and finishing rates are specified. These ratings are largely impractical in marine installations. The required charging current is the sum of the charge rate plus anticipated loads during charging.
- f. Charge Voltage.** The majority of alternators have a fixed output of 14 volts, with some makes having the option of regulator adjustment up to around 14.8 volts for isolation diode volt drop compensation. Charge voltage is probably the single most important factor on board.
- g. Alternator Output Current Selection.** From the power analysis table we have calculated the maximum current consumption. Added to this is a 20% margin for battery losses giving a final charging value. One popular opinion is that alternator rating should be approximately 30% of battery capacity. In practice this is at best optimistic and difficult to achieve. I always specify and install an 80 amp (Bosch) alternator, which is around the largest rating possible without going into over-priced or exotic alternators of greater ratings. I avoid where possible installing a battery bank in excess of 300 amp-hours and usually fit a bank of two six volt cells rated at 230 amp-hours. With a suitable regulator system I have never found this to be inadequate for vessel charging or load requirements. You can go and fit large output units but there are always the economic considerations.
- h. Marine Alternators.** Marine alternators are essentially enclosed, and ignition protected. This prevents accidental ignition of hazardous vapours. Windings are also protected to a higher standard by epoxy impregnation and output characteristics are generally similar to automotive types. Manufactured marine units also have a corrosion resistant paint finish (which is rarely a problem), and designed for higher ambient operating temperatures.
- i. Marinised Alternators.** An alternator can be marinised to a reasonable degree. If you wish to marinise and improve your alternator perform the following:
- (1) **Bearings.** Bearings should be of the totally enclosed type. Replace if they are not.
 - (2) **Windings.** Windings should be sprayed or encapsulated with a high grade insulating spray.
 - (3) **Diode Plate.** The back of the diode plate can also be sprayed to provide an insulating coating, preventing the ingress of moist salt laden air and dust which can short out diodes and connections.

- j. **Surge Protection.** Some alternators are provided with separate surge protection units. Lucas/CAV alternators have these units available. Some series of Lucas alternators also incorporate a surge protection avalanche diode within the alternator (ACR & A115/133 range). This protects the main output transistor in the regulator. Unfortunately, very few alternators are fitted with any surge protection.

(a) LUCAS SURGE PROTECTION UNIT



(b) LUCAS AVALANCHE DIODE REGULATOR PROTECTION

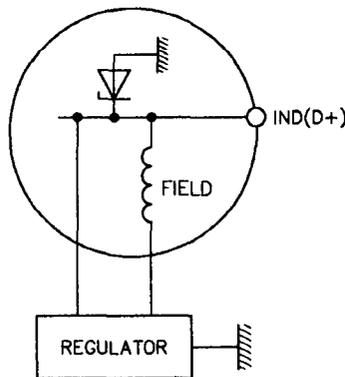


Figure 2-5. Lucas Surge Protection.

- k. **High Output Alternators.** It is regrettably a fact of life that many so called marine electrical people push the idea of a large output alternator, typically 130 amps plus, to solve battery charging problems. They are extraordinarily expensive, and really only mask the problem. Be warned! This will not resolve your problems. It is rare to require an alternator rated at over 80 amps. This is the typical automotive electrician's answer, but not a marine one. The real solution is in the regulator, which is a considerably cheaper and more reliable option.
- l. **Outboard Motor Alternators.** Outboard motors are commonly installed on many multihull vessels up to around 40 foot and charging problems are commonplace. Outboards have a flywheel driven alternator, and they are generally low in output, typically around 10-15 amps. Some manufacturers do have units up to around 20 amps (Yamaha) and this is still well short of the output required in cruising.

2.6. Alternator Installation. Optimum service life and reliability can only be achieved by correctly installing the alternator. The following factors must be considered during installation:

- a. **Alignment.** It is essential that the alternator drive pulley and the engine drive pulley be correctly aligned. Misalignment of pulleys can impose twisting and friction on drive belts and additional side loading on bearings. Both can cause premature failure.
- b. **Drive Pulleys.** Drive pulleys between the alternator and the engine must be of the same cross-section. Differences will cause belt overheating and premature failure. Ideally the normal split automotive type pulleys on some alternators should be replaced by solid pulleys of the correct ratio.
- c. **Drive Belt Tension.** Belts must be correctly tensioned. Maximum deflection must not exceed 10 mm. When a new belt is fitted the deflection should be re-adjusted after 1 hour of operation and again after 10 hours. Belts will stretch in during this period:
 - (1) **Under-tensioning.** This causes belt overheating and stretching, as well as slipping and subsequent undercharging. The excess heat generated also heats up pulleys and the high heat level conducts along the rotor shaft to the bearing, melting bearing lubricating grease and increasing the risk of premature bearing failure.
 - (2) **Over-tensioning.** This causes excessive bearing side loads which leads to premature bearing failure. Signs of this condition will be characterised by sooty looking deposits around the belt area, and wear on the edges of the belt.
- d. **Drive Belts.** Belts must be of the correct cross section to match the pulleys. Castellated belts are the ideal in the engine area as they dissipate heat easily. If multiple belts are used, always renew all belts together to avoid varying tensions between them. In any alternator over 80 amps in rating, a dual belt system should be used, as a single belt will not be able to cope with the mechanical loads applied at higher outputs.

- e. **Ventilation.** Engine compartments offer very few ventilation options. Ideally a cooling supply fan should be fitted to run when the engine is operating. An alternator, similar to electrical cable, is derated in high temperatures. The fan outlet should be directed to the alternator. Many alternator failures occur when boost charging systems are installed because they run at near maximum output for a period in high ambient temperatures. Always ensure when fitting an additional alternator that the fan is rotating in the correct direction.
- f. **Mountings.** Mountings are a constant source of problems, observe the following:
 - (1) **Tensioning.** When tensioning the alternator, always adjust both the adjustment bolt and the pivot bolt. Failure to tighten the pivot bolt is common and this causes alternator twisting and vibration. Vibration fatigues the bracket or mounting and causes it to fracture. Additionally this can cause undercharging and radio interference.
 - (2) **Adjustment Arm.** Ensure that the slide adjustment arm is robust. Many engines have a reasonable level of vibration which fatigues the slide and breaks it. Volvo engines seem to be notorious for this from experience. I would always recommend the uprating of the arm. Take off the old one and have another one custom made.
- g. **Warning Light.** The light circuit is not simply for indicating failure. The lamp provides excitation to the alternator. In many cases an alternator will not operate if the lamp has failed and this is because the remanent voltage or residual magnetism has dissipated. Ideally a lamp should be in the range of 2-5 watts. Undersized lamps are often characterised by the need to "rev" the engine to get the alternator to "kick" in. This is often highly visible with alternator driven tachometers. Many newer engine panels have a printed circuit board type of alarm panel. I always recommend where possible a separate light.
- h. **Interference Suppression.** Alternator diode bridges create noise (RFI) which can be heard on communications or electronics equipment. Always install an interference suppression capacitor. As a standard, install a 2.2 micro farad suppressor. Suppression is covered in detail in a later chapter.

2.7. Alternator Drive Pulley Selection. Ideally, maximum alternator output is required at a minimum possible engine speed. This is typically a few hundred revs/min above idle speed. Manufacturers install alternators and pulleys based on the premise that the engine is only run to propel the vessel, when in fact engines spend more time functioning as battery chargers, at low engine revolutions. Alternators have three speed levels that must be considered and the aim is to get full output at the lower speeds:

- a. **Cut-in Speed.** This is the speed at which a voltage will be generated.
- b. **Full Output Operating Speed.** This is the speed where full rated output can be achieved.

- c. **Maximum Output Speed.** This is the maximum speed allowed for the alternator, otherwise destruction will occur.
- d. **Pulley Selection.** An alternator is rated with a peak output at 2,300 revs/min. At a typical engine speed of 900 revs/min and a minimum required alternator speed of 2,300, a pulley ratio of approximately 2.5:1 is required. The maximum speed in this case has a 10,000 rev/min rating. Maximum engine speed is 2,300 in this case, so 2,300 multiplied by 2.5 = 4,000 revs/min. This falls well within operating speeds limits and is acceptable. A pulley giving that ratio would suit the service required.
- e. **Selection Table.** Table 2-1 gives varying pulley ratios with an alternator pulley of 2.5 inches.

Table 2-1. Drive Pulley Selection Table.

Engine Pulley	Pulley Ratio	Engine RPM	Alternator RPM
5 inch	2:1	2000	4000
6 inch	2.4:1	1660	4000
7 inch	2.8:1	1430	4000
8 inch	3.2:1	1250	4000

f. **Alternator Characteristics.** The graph below illustrates the relationship between output current, efficiency, torque and HP against rotor revolutions. The optimum speed can be selected from these characteristics. The performance curves and characteristics illustrated are for a Lestek high output alternator, and for a 9135 series 135 amp alternator.

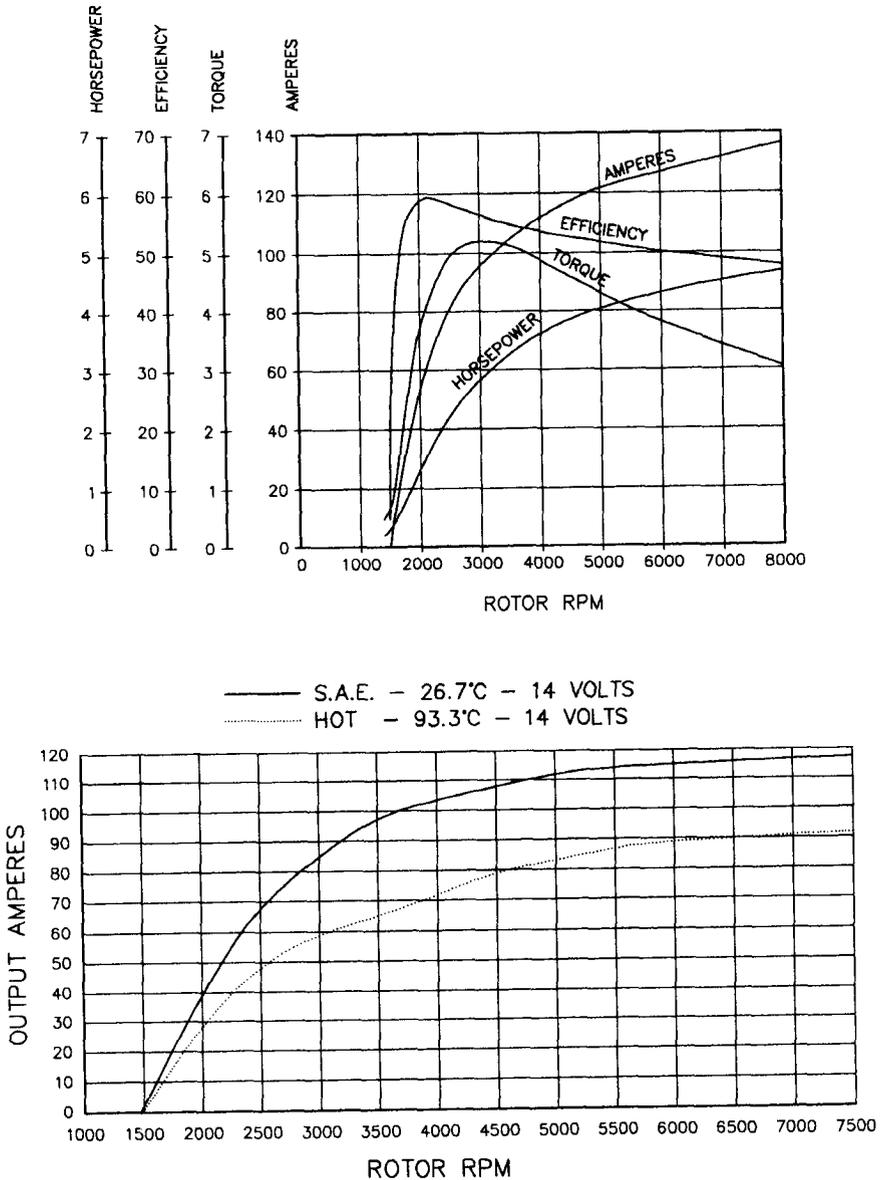


Figure 2-6. Alternator Output Characteristics.

2.8. Alternator Maintenance. Many alternator failures can be avoided by performing basic maintenance tasks. The following tasks should be carried out:

- a. **Drive Belts.** (Monthly) Check as follows:
 - (1) Check and adjust tension. Deflection 10mm maximum.
 - (2) Examine for cuts, uneven wear or fatigue cracks.
 - (3) Ensure belts are clean, with no oil or grease.
- b. **Connections.** (Monthly) Check as follows:
 - (1) Clean and tighten all alternator terminals.
 - (2) Check cable and connectors for fatigue.
- c. **Vibration.** (Monthly) Check as follows:
 - (1) Check alternator for vibration when running.
 - (2) Examine mounts for fatigue cracks.
- d. **Bearings.** (1500 Operating hours) Check as follows:
 - (1) Remove alternator and turn rotor. Listen for any bearing noises.
 - (2) Renew every 3000 hours or at major overhaul.
- e. **Brushes.** (1500 Operating Hours) Check as follows:
 - (1) Check brushes for excess or uneven wear.
 - (2) Check sliprings for scoring.
- f. **Cleaning.** (Yearly) Clean as follows:
 - (1) Wash sliprings, diode plate and brushgear with electrical solvent. Do not use any abrasives on sliprings, they must be cleaned only, as a film exists on them which is essential for brush contact.
 - (2) Wash out windings and dry.
- g. **Pre-cruise.** Take alternator to a quality marine/auto electrical workshop. Request the following tests:
 - (1) Test alternator output for maximum current.
 - (2) Check diodes.
 - (3) Clean windings, sliprings and brushgear.
 - (4) Renew bearings.
 - (5) Renew brushes.

2.9. Alternator Faults and Failures. Failures in alternators are primarily due to the following causes, many which are preventable with routine maintenance:

a. Diode Bridge Failures. Diode failures are generally attributable to the following causes:

- (1) **Reverse Polarity Connection.** This is a common cause. Reversal of the positive and negative leads will destroy the diodes.
- (2) **Short Circuiting Positive and Negative.** A short circuit will cause excess current to be drawn through the diodes and the subsequent failure of one or more of diodes, the most common cause here is reversing the battery connections.
- (3) **Surge.** This occurs if the charge circuit is interrupted, most commonly when an electrical changeover switch is accidentally opened. A high voltage surge is generated due to the inductive effect of the field and stator windings.
- (4) **Spikes.** This is a short duration high voltage transient. These are caused by inductive loads starting up, such as pumps. Voltages several times greater than the nominal voltage can appear. The most common spike is that from a lightning strike. Countermeasures are covered in the lightning protection chapter.

b. Winding Failures. Stator winding failures are usually due to the following causes:

- (1) **Overheating.** Normally due to insufficient ventilation at sustained high outputs, which causes insulation failure and intercoil short circuits.
- (2) **Stator Winding Short Circuit.** Due to mechanical winding damage, overheating or ingress of moisture.
- (3) **Rotor Winding.** Short circuit or ground fault due to overheating or over voltage if the voltage regulator fails.

c. Brushgear. Brushgear failures are not that common in a properly maintained alternator but failures are generally due to:

- (1) **Brushes.** Brushes worn and sparking, and characterised by fluctuating outputs, and radio interference.
- (2) **Sliprings.** Scoring and sparking due to build-ups of dust, also causing radio interference.

d. Bearing Failure. The first bearing to fail is normally the front pulley bearing. Rotation by hand will usually indicate grating or noise.

2.10. Alternator Fault Finding. Fault finding should be carried out in conjunction with charging system fault finding as described in Table 3-1, and is based on the following:

- a. **Check Output.** This initially depends on the lamp and the regulator. Using a voltmeter, check that the output across the main B+ terminal and negative rises to approximately 14 volts. No output indicates either total failure of alternator or regulator. Partial output indicates some diodes failed or a regulator fault.
- b. **Check Components.** The components are tested after confirming the function of the regulator. Initially I recommend removal of the alternator, and taking it to any good automotive electrician with a test bench if in port. This saves a considerable amount of time and effort. If you don't carry spares then you can do little. To get home with partial diode failure, the regulator may require disconnection, and a full field voltage applied to get maximum output.

2.11. Alternator Terminal Designations. Alternators have a variety of different terminal markings and these are listed in Table 2-2.

Table 2-2. Alternator Terminal Markings.

Make	Output	Negative	Field	Aux.	Tacho
Bosch	B+	D-	DF	D+/61	W
Lucas	B+	B-	F	IND/AL	W
Hitachi	BAT	E	F	L	
P-Rhone	+	-	DF	61	W
S Marchal	B+	D-	DF	61	
Motorola	+	-	F	AUX	AC
CAV	D+	D-	F	IND	
AC Delco	BAT	GND	F		
Niehoff	BAT+	BAT-	F	D+	X
Valeo	B+	D-		D+	W
Mitsubishi	B+	E	F	L	
Nip. Denso	B+	B	F	L	
Prestolite	POS +	GND		IND LT	AC TAP

2.12. Alternator Test Specifications. The following specifications are typical for a range of Bosch and Ingram alternators.

Table 2-3. Alternator Test Specifications.

Model	Output	Speed	Stator Resistance	Rotor Resistance
14V 35 A	10A	1300 rpm	0.24 Ohm	4.0 Ohm
	23A	2000 rpm		
	35A	6000 rpm		
14V 55 A	16A	1200 rpm	0.14 Ohm	4.0 Ohm
	36A	2000 rpm		
	55A	6000 rpm		

2.13. Alternator Remagnetisation. After dismantling or stripping down an alternator it is not uncommon to find it simply won't work at all. Before you hurriedly dismantle it again to locate a mistake in assembly perform the following checks:

- a. **Field Disconnect.** Disconnect the regulator field connection. (assuming you have installed a separate regulator or controller).
- b. **Manual Field Activation.** With the engine running at idle speed, and all electrical and electronics equipment off, temporarily touch the field connection to the following:
 - (1) **Positive Control.** (Bosch, Paris-Rhone, Motorola, new Sev-Marchal) If the field control is on the positive side, touch the lead to main alternator output terminal B+, or if a diode is fitted then to the diode battery output terminal.
 - (2) **Negative Control.** (Lucas, CAV, Hitachi) If the field control is on the negative side, touch the lead to the negative terminal or to the case.
- c. **Output.** If the alternator is operational the alternator will immediately give a full output, and you will hear the engine load up, and voltage will rise up to 16 volts. Only do this for a second or two. Reconnect the regulator back to normal. In many cases this will restore magnetism to the alternator and it will operate normally. If there is no or a low output after this test it generally indicates a fault in the alternator, and this is normally a faulty diode bridge, or the brushes are not seating on sliprings.
- d. **Warning Light.** Ensure the light is operating and on when the ignition switch is turned on. If not the following may be faulty:
 - a. Lamp fault, or seating badly if replaceable lamp.
 - b. Lamp connection fault.
 - c. Wire off D+ terminal, or connection loose.
 - d. Faulty alternator excitation diodes.

ALTERNATOR REGULATORS

3.0. Alternator Regulators. The regulator is the key to all alternator charging systems. The function of the regulator is to control the output of the alternator, and prevent the output from rising above a nominal set level, typically 14 volts, which would otherwise damage the battery, alternator and equipment:

- a. **Principles.** An alternator produces electricity by the rotation of a coil through a magnetic field and the output is controlled by varying the level of the field voltage. This is achieved by applying the field voltage through one brush and slip-ring to the rotor winding, and completing the circuit back through the other slip-ring and brush. Essentially the regulator is a closed loop controller, constantly monitoring the alternator output voltage and varying the field voltage in response to output variations.
- b. **Regulator Operating Range.** A regulator does not control the charging process significantly until battery charge level is approximately 50%. Prior to that a battery will absorb a large charge current and represents the working area of the battery. When the voltage of the battery rises to this threshold, the regulator starts limiting the voltage level. The charge current levels off as the voltage level rises, and this is called the regulation zone. Figure 3-1 illustrates this characteristic.

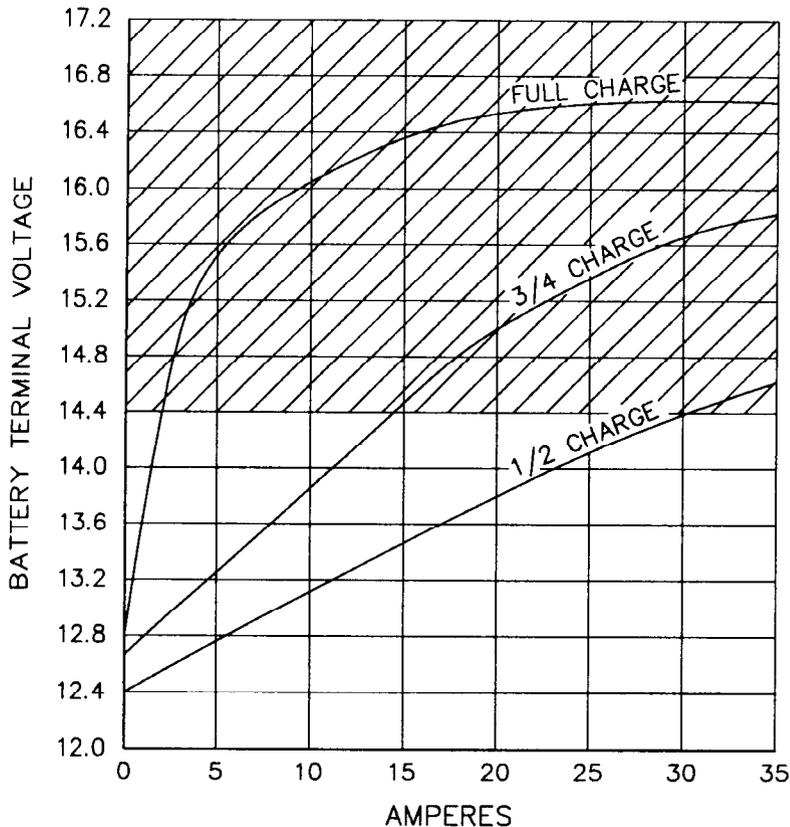


Figure 3-1. Regulator Operating Range.

- c. **Standard Regulators.** The traditional automotive alternator is fitted with a regulator designed for automotive service. This requires the replacement of a relatively small amount of discharged power, which it does in a short time period. The alternator then supplies the vehicle electrical loads during running periods. This is totally inadequate in vessel applications as all yachtsmen have experienced. To recharge a battery properly the charging system must overcome battery counter voltage, which increases as charging levels increase. The typical scenario is one of a high charge at initial start-up and then a rapidly decreasing current reading on the ammeter. As a result few yacht batteries are ever charged much above 70% of capacity. One of the many undesirable effects of standard regulators is that when a load is operating on the electrical system, charging current decreases. As an example, based on tests I have made with an alternator with a total output of 30 amps at 14 volts and a vessel electrical load of 24 amps, I found that only 6 amps was flowing into the battery with a terminal voltage of only 13.2 volts.

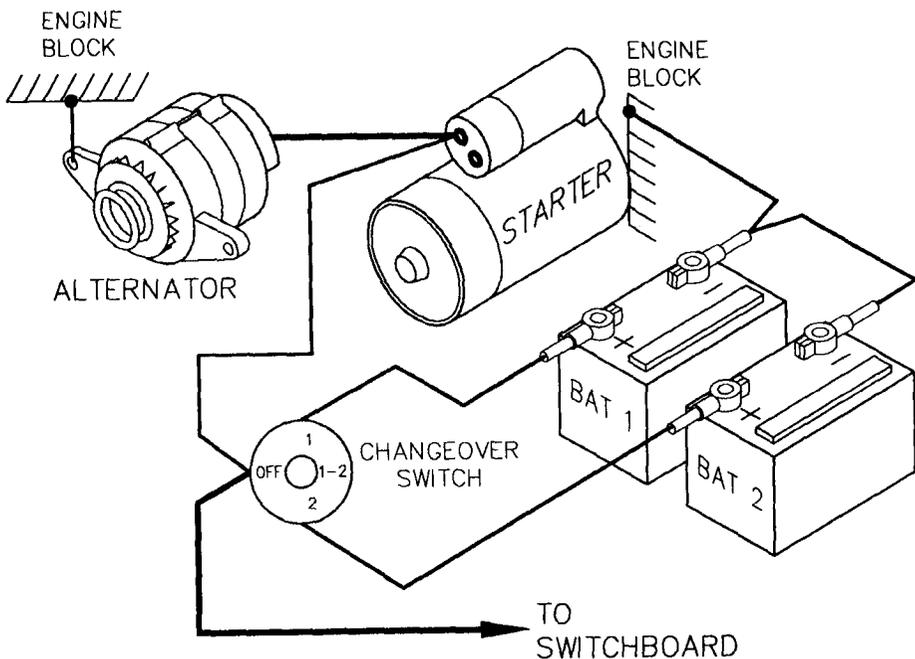


Figure 3-2. Standard Engine Charging Configuration.

3.1. Alternator Regulator Sensing. With any type of charging system there is a voltage drop between the alternator output terminal and the battery. With a nominal alternator output of 14 volts it is not uncommon to have a totally inadequate 13 volts at the battery. This voltage drop increases with an increase in current. Regulator sensing consists of the following configurations:

a. Machine Sensed. The machine sensed unit simply monitors the output terminal voltage and adjusts alternator output voltage to the nominal value, which is typically 14 volts.

(1) **Charge Circuit Voltage Drops.** The machine sensed regulator makes no compensation for charging circuit voltage drops. Voltage drops include inadequately rated terminals, cables and negative path back through the engine block.

(2) **Diode Isolators.** If a diode isolator charge distribution system is installed this also contributes a further drop which is typically 0.75 volt.

b. Battery Sensed. The battery sensed unit monitors the voltage at the battery terminals and adjusts the alternator output voltage to the nominal voltage.

(1) **Charge Circuit Voltage Drops.** The battery sensed regulator compensates for voltage drops across diodes and charge circuit cables. The regulator by sensing the battery terminal voltage varies the output from the alternator until the correct voltage is monitored at the battery. Some alternator manufacturers such as Bosch, Lucas, Prestolite and Sev-Marchal are introducing modifications so that regulators can be compensated with a separate sense connection that goes directly to the battery. Volvo have just introduced this on marine engine alternators and Lucas also have this on some models. Always install battery sensing if possible.

(2) **Caution.** In some cases the voltage drop between alternator terminals and battery may be considerable, and figures of 1.5 to 2 volts and above is not uncommon. It is sensible to check with a multimeter the output and battery voltage to find out the drop, ideally at full rated output current. An excessive volt drop is a fire risk, as excessive current can flow, and along with high ambient engine space temperatures literally melt and ignite the cable insulation, or typically first burn off the terminals. Check output terminal to see if it is hot.

c. Temperature Compensation. Very few alternator manufacturers incorporate temperature compensation. An electrolyte is temperature dependant. In hot climates charge voltages should be marginally decreased and in cold climates voltage should be increased. Regulators with compensation usually have it sensed at the regulator. In most vessels, the batteries are not always located near the engine so the regulator senses the engine compartment temperature and reduces charging output in compensation. This is not the actual ambient temperature of the batteries which is the temperature compensation required.

3.2. Alternator Regulator Types. It is extremely important to distinguish between a regulator and a controller. There are a number of new devices on the market which do not fit into the regulator definition.

- a. **Regulator Function.** A regulator is a fully automatic device which ensures a stable output from the alternator. What follows is crucial to understanding what a regulator does, as this is frequently forgotten with disastrous results. The primary function of a regulator is to prevent overcharging of the battery and damage to the alternator and this point should be considered when selecting a controller.
- b. **Alternator Control Devices.** There are four main categories of alternator control devices which will be covered as follows:
 - (1) **Standard Regulators.** These are factory fitted to alternators,
 - (2) **Cycle Regulators.** These devices use a cyclic regulator control principle,
 - (3) **Regulator Controllers.** These devices either parallel connect or over-ride existing standard regulators,
 - (4) **Manual Controllers.** These devices have no regulator function and control alternator output manually by operator control.

3.3. Standard Regulators. The standard alternator regulator is a simple and inexpensive electronic device. The contents are a simple voltage regulator device with associated circuitry. They are normally installed as an integral part of the alternator, or incorporated with the brushgear as a removable module, or located externally on the engine or an adjacent bulkhead. The preferable arrangement is to have a separate regulator mounted on an adjacent bulkhead to minimise engine heat and vibration damage.

3.4. Regulator Polarity. Regulators and field windings have two possible field polarities. It is important to know the difference when installing different regulators or testing regulator function. The two types are as follows:

- a. **Positive Polarity.** The positive regulator controls a positive excitation voltage. Inside the alternator, one end of the field is connected to the negative polarity. Alternators with this configuration include Bosch, Motorola, Ingram, Sev-Marchal (older models).
 - (1) **Polarity Test.** To test, use a multimeter on the Ohms x 1 range and connect across the field connection and an unpainted part of the alternator case or negative output terminal.
 - (2) **Meter Reading.** The reading should be in the range of 3 to 8 Ohms.

b. **Negative Polarity.** The negative regulator controls a negative excitation voltage. Inside the alternator one end of the field is connected to the positive polarity. Alternators with this configuration include Hitachi, Lucas A127, ACR 17-25 & AC5, CAV, Paris-Rhone, New model Sev-Marchal and Valeo, AC Delco, Mitsubishi.

- (1) **Polarity Test.** To test, use a multimeter on the Ohms x 1 range and connect across the field connection and the alternator positive terminal.
- (2) **Meter Reading.** The reading should be in the range of 3 to 8 Ohms.

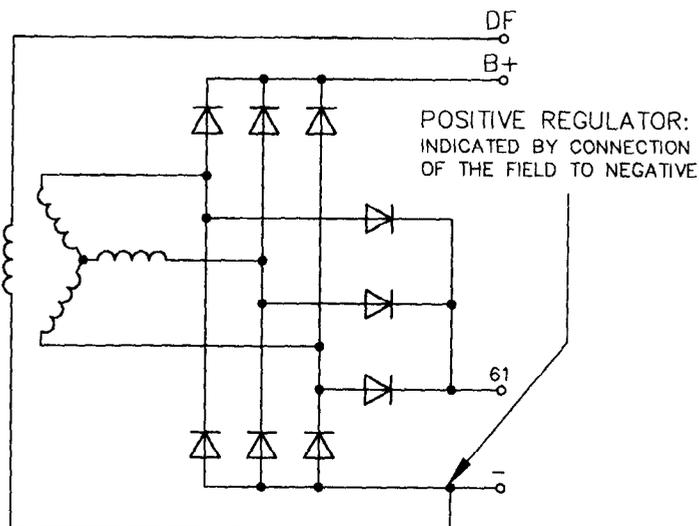
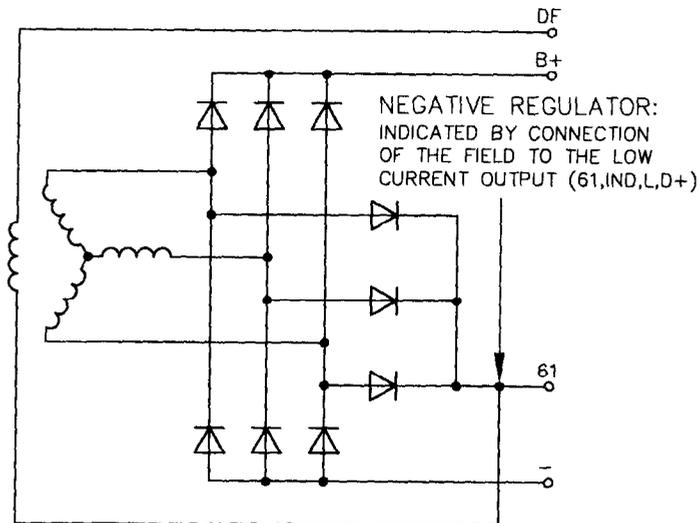


Figure 3-3. Alternator Regulator Field Polarity.

3.5. Regulator Removal. If a regulator must be removed or checked, certain procedures should be used to avoid damage. The following diagrams illustrate various alternators for the main engine groupings and disassembly procedure. Ideally a separate regulator should be installed on the bulkhead that makes replacement simple and inexpensive, and facilitates testing:

- a. **Bosch (K1/N1 Series).** Dismantle as follows:
 - (1) Unscrew the two screws retaining the regulator.
 - (2) Carefully lift the regulator up and out. Be careful not to damage the brushes.
 - (3) Disconnect the (D+) lead from the back of the regulator.

- b. **Bosch (EP Series 85 Amp).** Removal as per step 1 & 2 above. This alternator has a regulator with both a battery sense connection and warning lamp connection. Do not reverse leads as the warning light circuit will be damaged. Maximum lamp is 2 watts. There is no connection on back of brushgear, as contacts are via spring loaded assembly.
 - (1) Cut off left side connection located under 'L' marking, which goes to one brush. Cut off centre connection to other brush.
 - (2) Solder a wire to lower brush-holder and take out to a negative connection, either a terminal or under brushgear RHS holding screw adjacent to 'S' marking.
 - (3) Solder another wire to remaining brush-holder and lead out of case for connection to new regulator field connection.

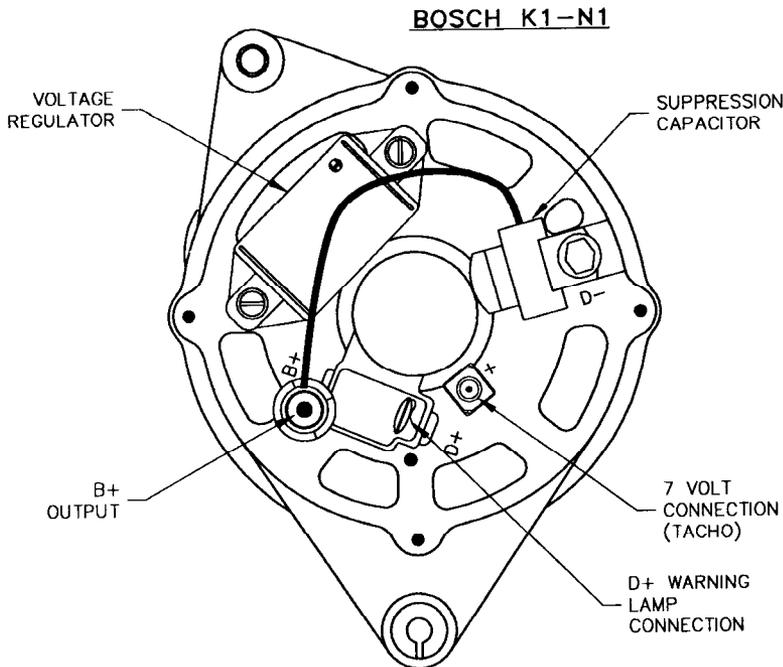


Figure 3-4. Bosch Alternator.

b. **Lucas A127.** This is usually a standard type fitted to Perkins engines. There are a large number of Lucas alternators around, and all are different. This procedure is for both removal and conversion to an external regulator.

- (1) Unscrew and remove the two screws securing the integral regulator and brushgear to the alternator housing.
- (2) Carefully lever open the two halves of the regulator. This is held together by a glue.
- (3) Cut and disconnect the three joining links from the brushes.
- (4) Solder on a new wire to the spring loaded connector immediately below the inner brush-holder. You must use a special solder to do this, as normal solders will not work. (RS Stock Number 555-099) Run it out through the cover for connection to the new regulator. This is the field control connection.
- (5) Place the two regulator halves together and refit into the alternator.

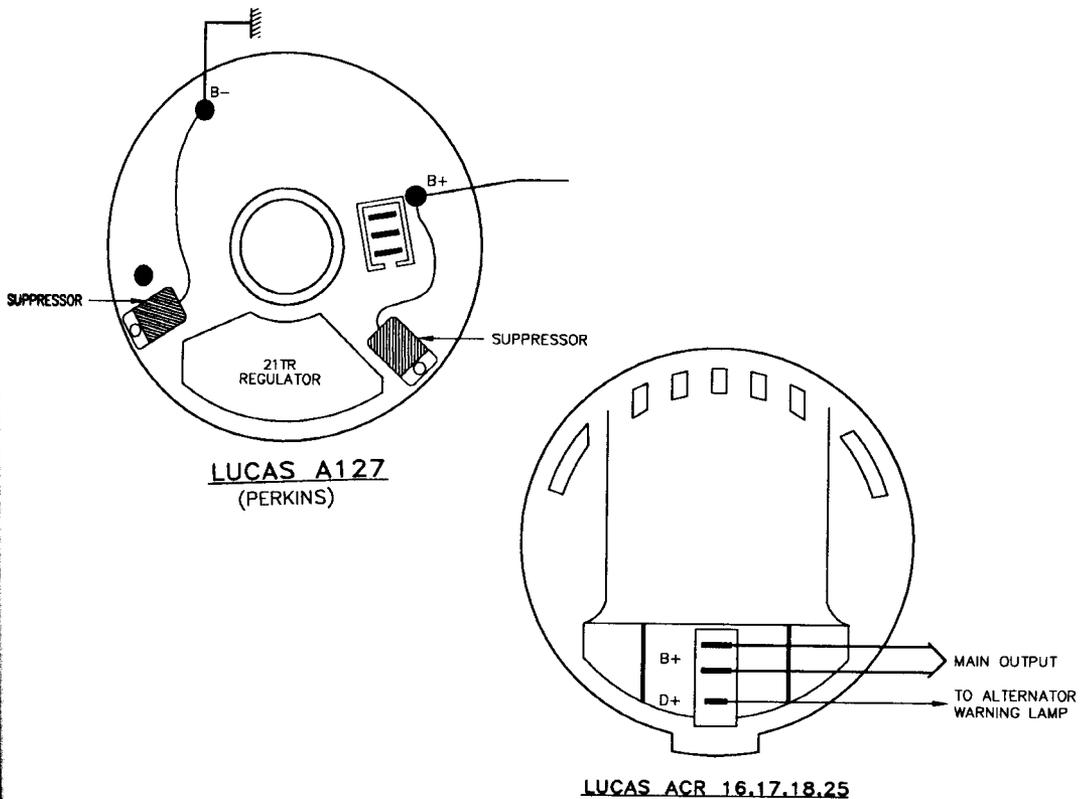


Figure 3-5. Lucas Alternator.

c. **Paris-Rhone/Valeo.** Usually a standard type fitted to Volvo engines. It should be noted that Paris-Rhone and Valeo are now all the same as Valeo alternators. There are some differences in the design. Use the following procedure to disconnect and install a new external regulator system, or replace the existing one:

- (1) Unscrew and remove the four screws securing the regulator to the casing.
- (2) There are four cables leading from the regulator (5 on the new Valeo). If you are replacing the regulator with an external type, the cables should be cut off at the regulator, as the regulator and housing acts as a spark arrester cover for the brushgear.
- (3) Remove the negative cable to the regulator entirely.
- (4) The cable running internally under the plastic cover to terminal 61 should be soldered to one of the brush-holder connections. This cable was initially connected to the regulator until cut off.
- (5) Solder on a wire to the remaining brush-holder and run it out through the cover for connection to the new regulator. This is the field control connection.

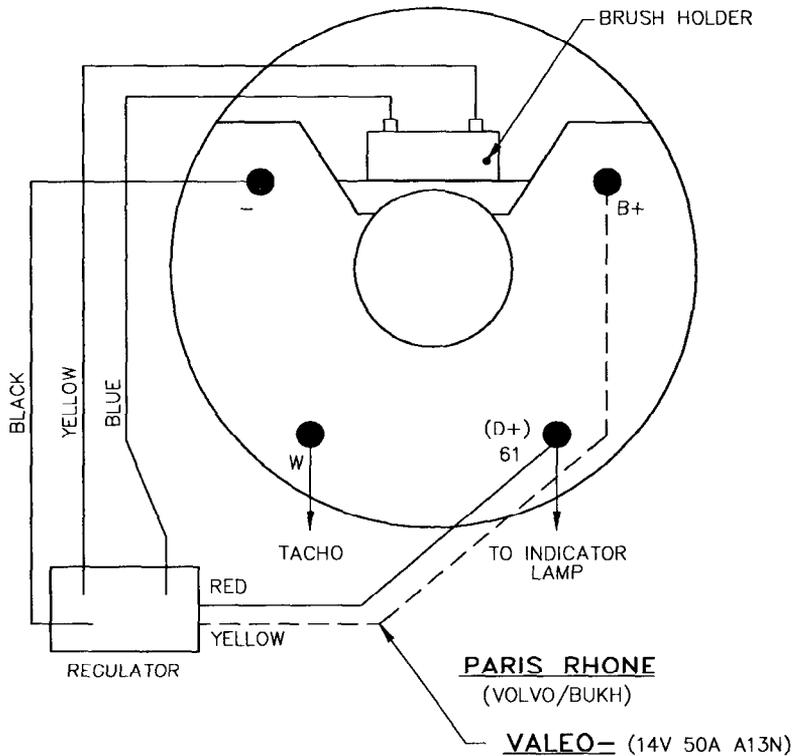
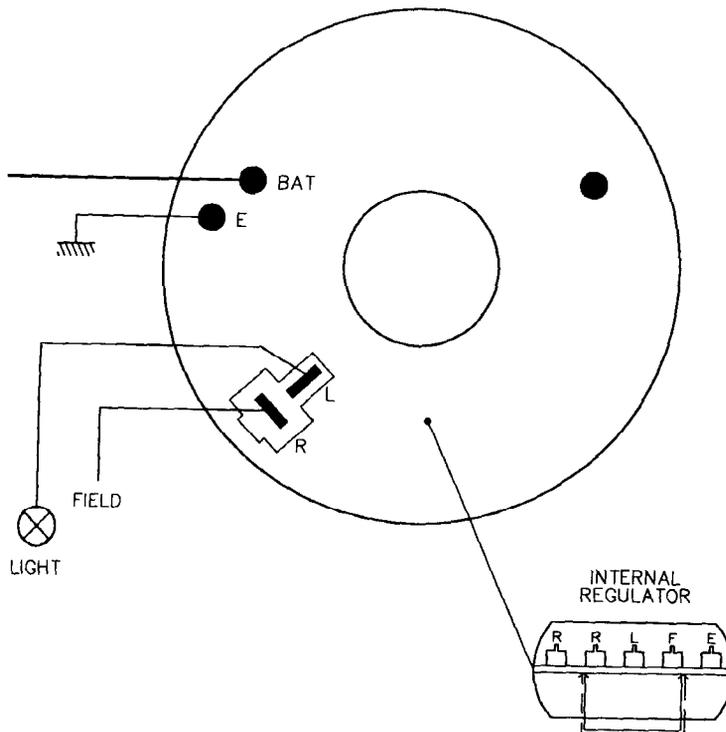


Figure 3-6. Paris-Rhone/Valeo Alternator.

d. **Hitachi.** This is a standard alternator type fitted to Yanmar engines. Models LR 135-74 35A, LR 155-20 55A and LR 135-105 35A:

- (1) Remove the rear casing from the alternator. These are generally extremely tightly torqued up screws, so use the correct size of screwdriver.
- (2) Carefully cut off the connections to the existing regulator. There are five in total.
- (3) Solder on a 1.5 mm bridging wire between the R and F terminals as illustrated.
- (4) Replace the rear casing.
- (5) Connect the external field connection to the socket on the rear of the alternator. A cable and plug is normally fitted and can be removed.



HITACHI (YANMAR)

LR 135-74 35A
LR 155-20 55A
LR 135-105 35A

Figure 3-7. Hitachi Alternator.

e. **Motorola.** Usually a standard alternator type fitted to Nanni and Universal engines and is a Model 9AR. Remove as follows:

- (1) Unscrew and remove the two retaining screws holding in the existing regulator.
- (2) Either cut, or remove the two cables connecting the regulator to the alternator.
- (3) Fit a new wire to the vacated lower terminal and run it out through the cover for connection to the new regulator. This is the field control connection.
- (4) Refit the old regulator and housing which acts as a spark arrester cover for the brushgear.

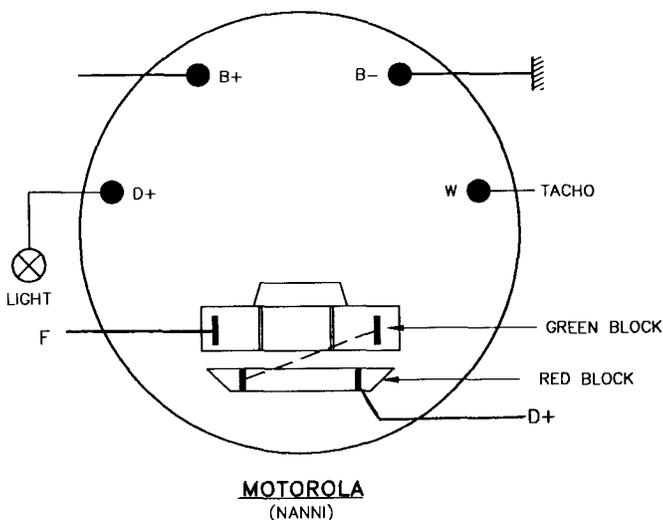
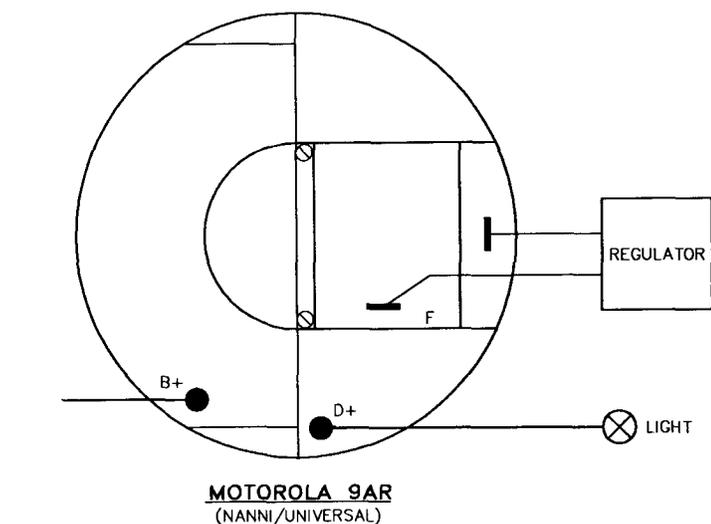
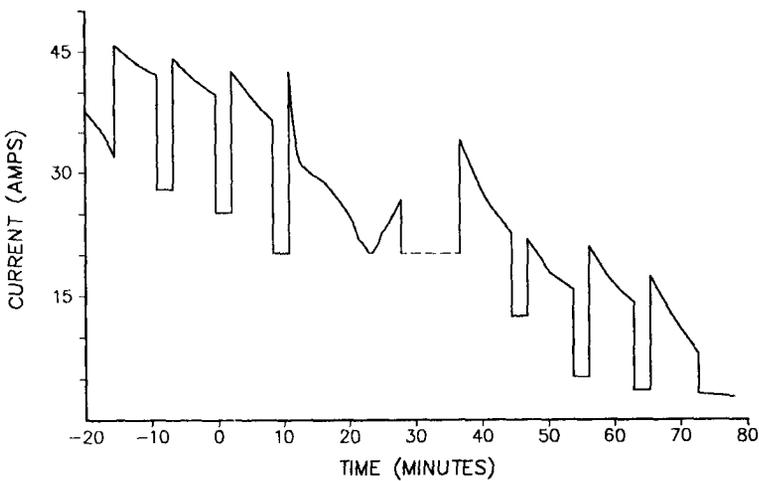
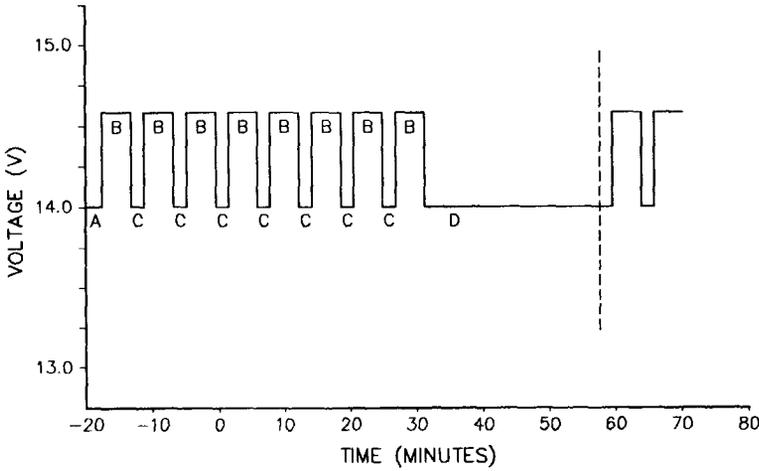
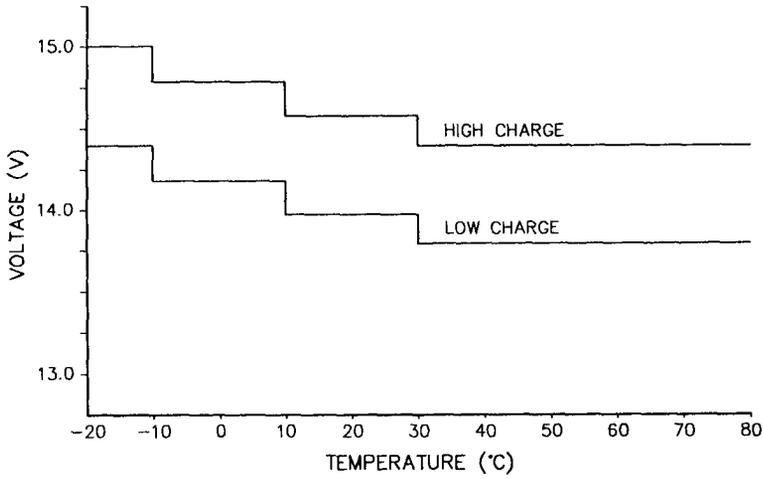


Figure 3-8. Motorola Alternator.

3.6. Cycle Regulators. The most important charging regulator development has been the TWC Regulator from Sweden and I have installed many hundreds successfully in yachts ranging from BOC entrants to cruising and racing yachts of all sizes. A recent UK magazine survey of ocean cruising yachts showed more than 40% of vessels now have such intelligent regulators, and they are almost standard on Whitbread entrants. The TWC regulator consists of a patented, purpose designed microchip with a charging program installed. Like the machine sensed regulator, the TWC monitors the alternator output voltage. Being battery sensed it also monitors the battery voltage, and compensates for the difference between them. The TWC also has an input from a temperature sensor located adjacent to the batteries, and uses this value in calculating charging voltage. The TWC has a charging program consisting of eight phases. The alternating high and low charging voltage phases effectively exercise the battery. This has a similar result to that from periodic equalisation charges, which has a stirring effect that stops the charge being held close to plates and enables complete electrolyte plate percolation and therefore complete charging. After each low voltage phase, a short duration high current surge is applied which causes a stirring action within the electrolyte, assisting in limiting sulphation, and breaking up sulphate deposits:

a. TWC Cycle Phases. The main cycle phases are illustrated in Figure 3-11 and are as follows:

- (1) **Phase A.** Charging at a low charge level of 13.8 V.
- (2) **Phase B.** Charge ceases, battery voltage measured under load.
- (3) **Phase C.** Charging at a high charge level of 14.6 V for 12 minute period if voltage is below a preset level.
- (4) **Phase D.** Charging decreases to 13.8 V for a two minute period, prior to next measurement phase.
- (5) **Phase E.** Charge ceases, battery voltage measured under load. If required the cycle continues for a further 12 minutes on high charge. If measured voltage exceeds preset level, the TWC goes into a compensating charge mode.
- (6) **Phase F.** Extended charging period, when alternator output is reduced. Time metering ceases and charging period extends until normal conditions resume.
- (7) **Phase G.** Rest period, automatically interrupts charging after eight 12-minute cycles are completed, or if preset level is exceeded. A compensating charge period then begins.
- (8) **Phase H.** Compensating charge period extension after heavy discharge prior to resuming Phase A. Gassing is eliminated by one hour low charge level.
- (9) **Phase I.** After the one hour rest period, battery status is measured and if required a new cycle period starts.



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Figure 3-9. TWC Charging Program Cycle Phases.

- b. **TWC Alarm Function.** Unlike most alternator warning lights, the TWC has a definite monitoring function with the light flashing either slowly or fast. Normal alternator and regulator system warning lights come on only if a drive belt breaks or the alternator fails. The flashing light codes of the TWC are as follows:

- (1) **Slow Flash.** If the electrical system draws more current than the alternator can supply, the TWC indicates this condition on the indicator lamp (one flash per second). This can be due to engine speed too low, too many electrical accessories operating, a faulty alternator, a TWC sensor has become detached or an over-voltage condition exists due to a faulty regulator or ground leakage. The alarm is usually cleared by increasing engine speed so that alternator is at full output speed, or switching off some equipment to reduce the load. An engine running at low speed is often thought to be charging the battery. In fact the opposite is often the case if a number of accessories are operating. It should be noted also that batteries in a heavily discharged condition will activate the slow flash function for up to 20 minutes.
- (2) **Fast Flash.** If charging circuit losses increase to abnormally high levels due to oxidation or corrosion of terminals and connections, the warning lamp flashes fast (three per second) to indicate the condition. Excessive voltage drops represent a fire hazard as cables may overheat, melt or ignite the insulation.

- c. **Other Features.** If the ignition is switched off, the TWC remembers where it was within the charging cycle, and if the engine restarts within an hour, will automatically continue where it left off. After a one hour period the unit switches off, and consumes only 15 milliamps in this monitoring phase. If the alternator output voltage decreases such as at engine idle speeds, the TWC ceases timing the charging phases, and resumes again when the voltage rises with increases engine speed, and full alternator output.

3.7. Adverc Cycle Regulator. This UK manufactured regulator utilises similar principles to the TWC regulator but has a number of different features. Unlike the single control chip TWC, this device is a multi chip device. A cycle program is also the basis of the charging system:

- a. **Cycle Period.** The cycle periods on the Adverc system consist of four 20 minute intervals followed by a one hour rest period. Voltage levels used within the charging cycle are a normal charge rate of 14.0 volts, and a high level of 14.5 volts.
- b. **Temperature Compensation.** Temperature compensation also takes place but where the TWC is a stepped characteristic, the Adverc has a linear one.
- c. **Warning System.** The Adverc system also has a light warning system, with indication given for low and high voltage conditions or a loss of sense leads.

3.8. Ample Power 3-Step Regulator. The Ample Power three step device uses a cycle type program, that is fully automatic, and operates based on the four charging cycles of bulk charge, absorption, float and equalisation. Battery temperature compensation is incorporated. There is however a user adjustable setting of step set points. The unit consists of a timer circuit rather than an intelligent program chip, and is coupled with appropriate sensing circuits. Cycles are as follows:

- a. **Charge Program.** The regulator has the following features:
 - (1) **Step 1.** Battery voltage is raised to 14.4 volts. The time required to reach this level depends on the initial battery level and output speed of the alternator.
 - (2) **Step 2.** Charge level is maintained at 14.4 volts for a period.
 - (3) **Step 3.** The charge level reduces to a float charge of 13.8 volts.
- b. **Protection Features.** The device has a master timing circuit that will automatically cease charging if long periods of charging at 14.4 volts occurs. Also charging is cut off if the battery sense lead detaches or breaks.

3.9. Alternator Manual Control Devices. Manual devices are those which require total operator control of the alternator output without regulation. Some handbooks give information on how to make your own controllers. From personal experience, once these home grown controllers and circuits are installed, it's a cremation for the charging system, batteries and alternator not too far into the future. There is no such thing as a cheap solution, and if you really care about your power system, don't risk it. There is no sense in having and relying on electronics worth thousands only to balk at paying relatively small sums to improve charging. The following control methods should be used at your own risk. Whilst there are many around who boast how reliable and cheap they are, I do not mind making a very nice living thank you very much, off the majority who have subsequent problems. The savings initially achieved on these methods are more than negated by one mishap and is often the case shortened battery life through overcharging and plate damage.

- a. **Field Switches.** A typical manual method is the switch directly connected to the field connection. It simply puts on a full field voltage resulting in maximum alternator output. The results can be quite spectacular and is very damaging to both battery and alternator. Once while crossing a dangerous bar on a friends vessel, he casually flicked a switch, which was followed by sparks and smoke curling out of the engine compartment. After investigation I found this same set-up. Potentially a disaster at the time.
- b. **Field Rheostats.** The most common type of control is the rheostat. A rheostat is simply a variable resistance rated for the field current. The term rheostat is still in common usage and low value variable resistances are generally termed potentiometers. Operation is totally reliant on operator control, with no safety cutouts or regulation. As a general alternator charging control it is not recommended, as both alternator and battery are easily and commonly damaged.

3.10. Alternator Controllers. Controllers are devices that require the yacht owner to manually select or partially over-ride the existing regulator to fast charge.

- a. **Operating Principles.** Controllers are either direct regulator replacement units or are connected in parallel to the existing regulator. Some units have an ammeter to monitor output and require continual adjustment of field current to maintain required charge current level, but they do not monitor or take into account the high and damaging system voltages that are imposed while maintaining the initial high charging currents.
- b. **Precautions.** All controllers have some beneficial outcome, and can improve the charging process to varying degrees. There are however serious risks that must be considered to avoid serious damage:
 - (1) **Power System Disturbances.** If you apply excessive voltages or full alternator outputs spikes and surges can arise on the system that damage alternators and electronics equipment.
 - (2) **Battery Damage.** Forcing current into batteries above the natural ability to accept charge will simply damage plates, heat the battery up, and generate potentially explosive gases. Failure of automatic cut-outs, or forgetting about the regulator may cause all of the mentioned problems.
- c. **Efficiency.** At best these types of units can offer a 10-15% improvement which brings charge levels up to approximately 85% of nominal capacity.
- d. **Controller Types.** Some of the more common controllers on the market are as follows:
 - (1) **AutoMAC.** This regulator is parallel connected to the existing regulator. A potentiometer is used to adjust alternator current in conjunction with an ammeter. When a predetermined voltage is reached the unit automatically cuts off and existing regulator takes over. Failure of automatic cut-offs are relatively frequent with subsequent overcharging and battery damage.
 - (2) **Glename.** These devices involve the application of full alternator output until a preset voltage is reached, which then should automatically reduce voltage to selected value.
 - (3) **Kestrel 90 Alternator Controller.** This device is parallel connected to the existing regulator. When the engine starts, the controller activates and applies a boost charge level until a programmed time limit cuts the controller off and the normal regulator takes over.
 - (4) **Solent Chagemaster.** This device has a small dial to enable setting of voltage level up to 15.8 volts. The device has a user selectable "kickback" function that automatically drops voltage back to 13.8 volts on reaching set value. If you forget to select the function serious overcharging can occur.

3.11. Regulator Fault Finding. If your regulator, and that includes TWC, or any controller, is suspect then there is a simple test to check this. This is not difficult with external regulators but if an internal regulator is fitted, the alternator will need to be opened and a wire attached to a brush-holder. Switch off all electrical and electronic equipment at the switchboard circuit breaker before commencing test. **If in doubt, don't try it.**

- a. **Alternator Test.** Check that the alternator gives full output. If the alternator operates after testing then the regulator is suspect.
- b. **Rotor Testing.** If a regulator has failed, particularly where this has failed to an overcharge condition, prior to replacing the regulator, the rotor should be checked for damage. The test is as follows and is illustrated below:
 - (1) **Test Insulation Resistance.** Place one multimeter probe on a slipring, and the other on the rotor core. Resistance should be infinite or over-range.
 - (2) **Test Winding Resistance.** Place the multimeter probes on each slipring. Resistance should be around 4 ohms. If it is very high an open circuit may exist, and if very low, a coil short circuit may exist.
- c. **Auxiliary Diode Test.** On some occasions, the auxiliary diodes may fail. Put your multimeter on the 20 volt range and connect across 61/D+ and negative. If there is any reading, the diode may be faulty. Turn on the ignition key without starting. The reading should be around 1-2 volts. If less the wiring may be faulty, if higher, the diode may be faulty, there is excessive rotor resistance or bad connections.

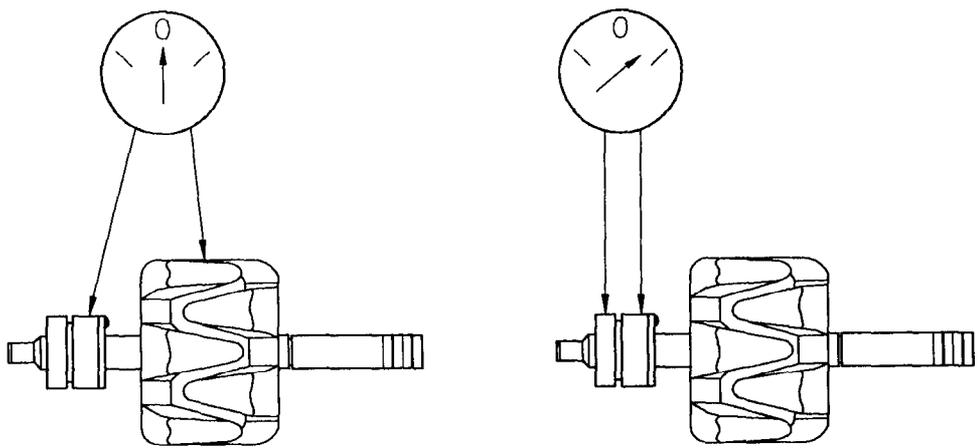


Figure 3-10. Rotor Testing.

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3.12. Charging System Configurations. The three principal systems are the changeover switch, the relay and the diode isolator.

a. Changeover Switch. The charging system on most engines uses the same cabling as the engine starter circuit. Basically it consists of a switch with 3 positions and off. The centre position parallels both battery banks. It is not uncommon to see both batteries left accidentally paralleled under load with flattening of both. Paralleling of a heavily discharged battery and a fully charged one during charging can also cause some instability in the charging as they both equalise.

- (1) **Switch Operation Under Load.** If a changeover switch is operated under load, the surge will probably destroy the alternator diodes. Most switches incorporate an auxiliary make before break contact for connection of field. This advanced field switching disconnects the field and therefore de-energises the alternator fractionally before opening of the main circuit. In reality this is rarely connected as most alternators have integral regulators and it is difficult to connect the switch into the field circuit.
- (2) **Surges.** If both batteries are paralleled during an engine start, sensitive electronics can be damaged by the surge.
- (3) **Circuit Resistance.** In most cases, the cables must run from the batteries to the switch location and back to the starter motor introducing voltage drops. Switches are notoriously unreliable and can introduce voltage drops into the circuit and total alternator or switch failure.

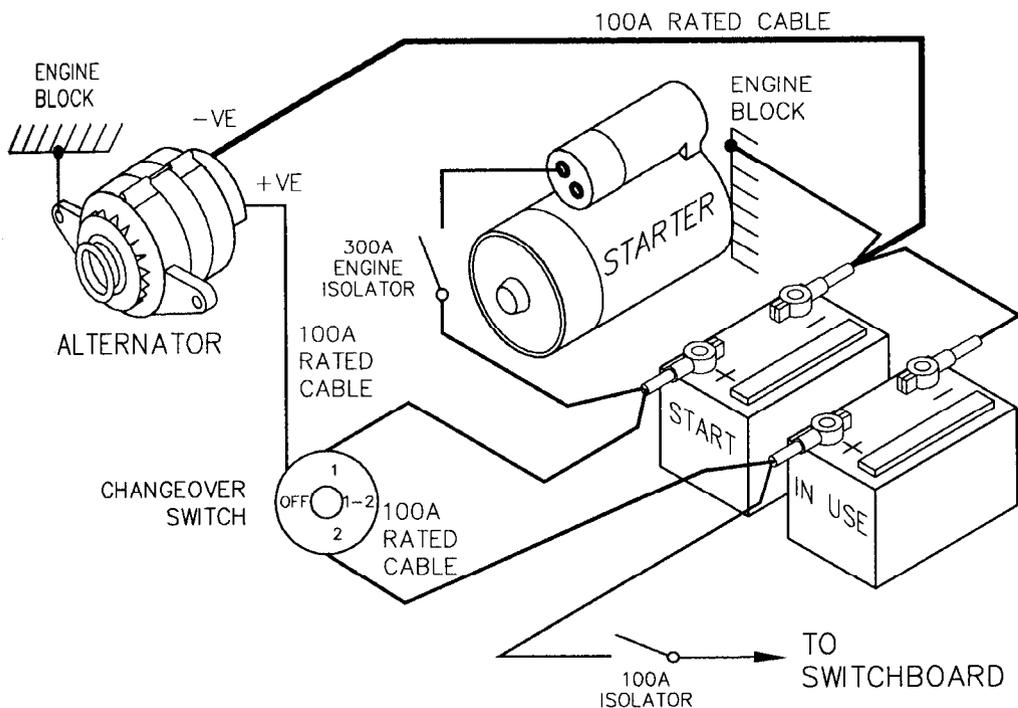


Figure 3-11. Changeover Switch Charging System.

- b. **Relay/Solenoid Configuration.** This system is able to improve on the switch system, and enables separation of the charging system from starting circuits. The relay or solenoid does offer a point of failure if incorrectly rated for the task. The relay interconnects both batteries during charging, and separates them when off. This prevents discharge between the batteries. The relay operating coil is interlocked with the ignition and energises when the key is turned on. When modifying the system, it is necessary to separate the charging cable from alternator to starter motor main terminal where it is usually connected. A cable is taken directly from the alternator output terminal to the relay as illustrated. Relay ratings should at least match the maximum rated output of the alternator. It is prudent to over-rate the relay. Relays are marketed in various forms, the most common being automotive solenoid types. Some are manufactured specifically for this task.

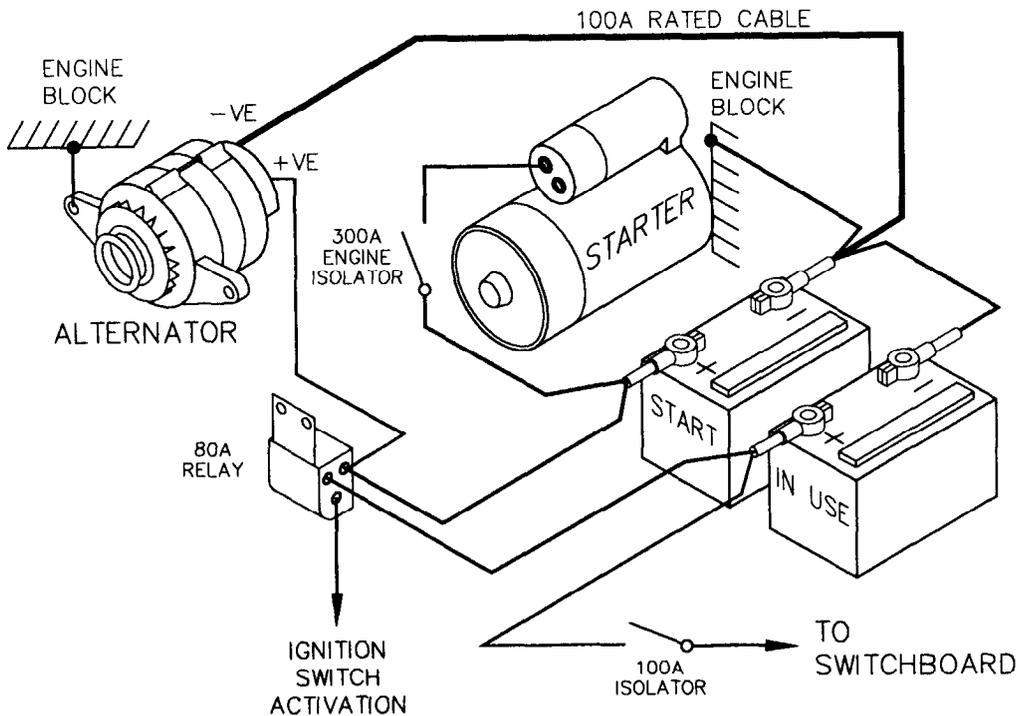


Figure 3-12. Relay Charging System Configuration.

c. **Diode System.** The diode system is the simplest configuration and the most reliable. It does have one disadvantage in some installations. A diode has an inherent voltage drop of typically .7-.8 volts. This is totally unacceptable in a charging circuit. If the alternator is machine sensed and does not have any provision for increasing the output in compensation, the diode should not be used. The diode is a simple and reliable electronic device. Essentially a diode isolator consists of two diodes with their inputs connected. They allow voltage to pass one way only, so that each battery has an output. This prevents any backfeeding between the batteries. Professionally built diode isolators should be used, such as the American manufactured Surepower isolator. They are mounted on heat sinks specifically designed for the maximum current carrying capacity and maximum heat dissipation. Home made units are notoriously unreliable and have given diode isolation systems an unfair reputation. The diode isolators must be rated for at least the maximum rating of the alternator, and if mounted in the engine compartment must be over-rated to compensate for the derating effect caused by engine heat. Not all diodes are heat sink mounted, Lucas manufacture a cylindrical, oil filled unit. Diodes should be mounted in the coolest area possible. Heat sink units should have the cooling fins in the vertical position to ensure maximum convection and cooling. The typical diode isolator charging system configuration is illustrated. Do not install switches in the cables from each output of the diode to the batteries as some recent magazine articles foolishly recommend. A diode is an isolator, so another mechanical switch is redundant.

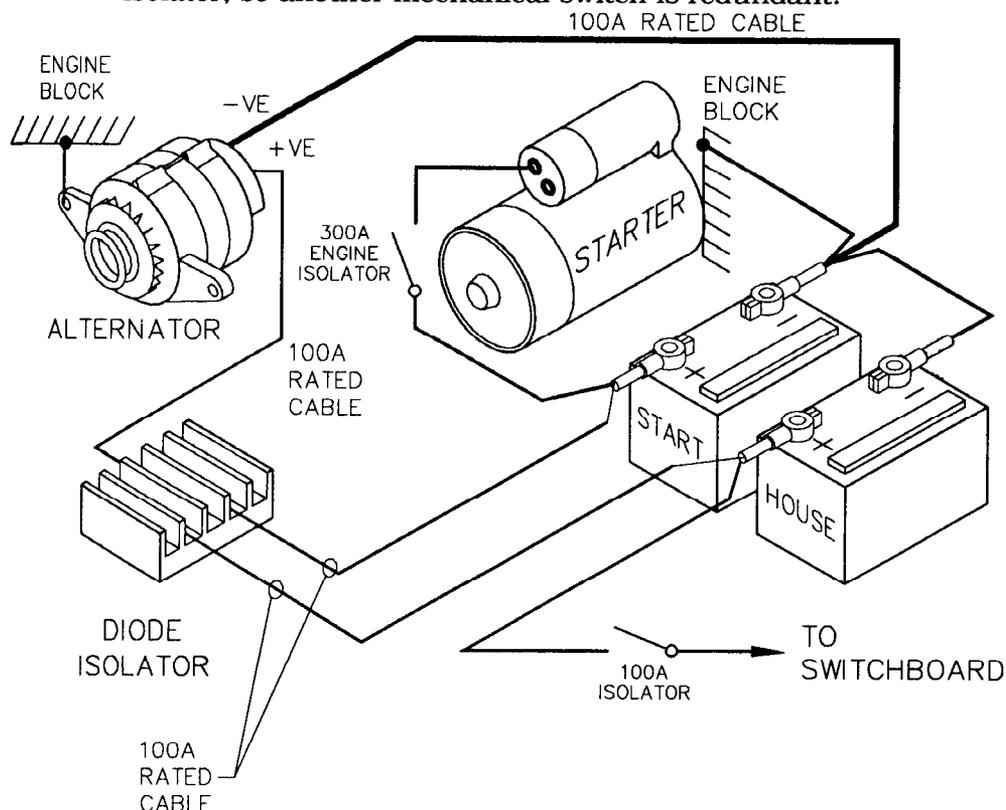


Figure 3-13. Diode Charging System Configuration.

d. **Automatic Charge Distributors.** These are characterised by two systems from Swedish company LEAB:

(1) **EDR Electronically Controlled Relays.** These devices allow charging of two or more batteries from one alternator or battery charger. One battery is selected as the priority unit, normally the house battery, although dedicated electric frig batteries are often lower. During charging, once the priority battery has reached the pre-set voltage level, the EDR automatically selects and connects the next battery. If during the charging, the priority bank charge level drops, the EDR will revert back to ensure that it remains fully charged.

(2) **CDB Charging Distributor.** This is a combination of functions, as charge distributor, battery isolator and regulator. The regulator function is not strictly true in that it has no control over field voltage. The device and connections are illustrated below.

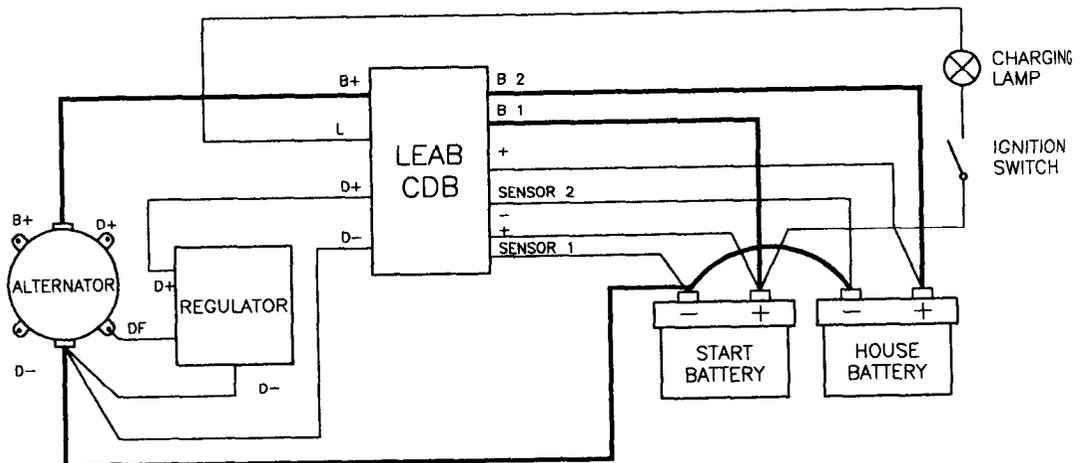


Figure 3-14. Automatic Charge Distributors.

3.13. Multiple Alternator Charging System Configurations. In many vessels the option of fitting a second alternator is taken. Generally charging problems could have been resolved without it but nevertheless the system does have advantages, mainly that of charging source redundancy. There are a number of different system configurations for multiple alternator installations which are as follows, and are illustrated in the schematic diagrams below:

- a. **Discrete Systems.** These systems usually have the original engine alternator charging the engine start battery only. The additional alternator, usually a higher rated type of 80 amps or greater charges the house batteries only. If there are more than one bank this may be split either through a diode isolator or a switch. Ideally the start battery alternator should be used to charge a third battery bank as it is very under utilised as start batteries require very little charging.
- b. **Cross Fed Systems.** These systems usually have each alternator charging a primary battery bank except that each alternator cross feeds to the other battery bank via a diode isolator. Ideally a fast charge device should still be used. This allows charging of both battery banks even if one alternator should fail.

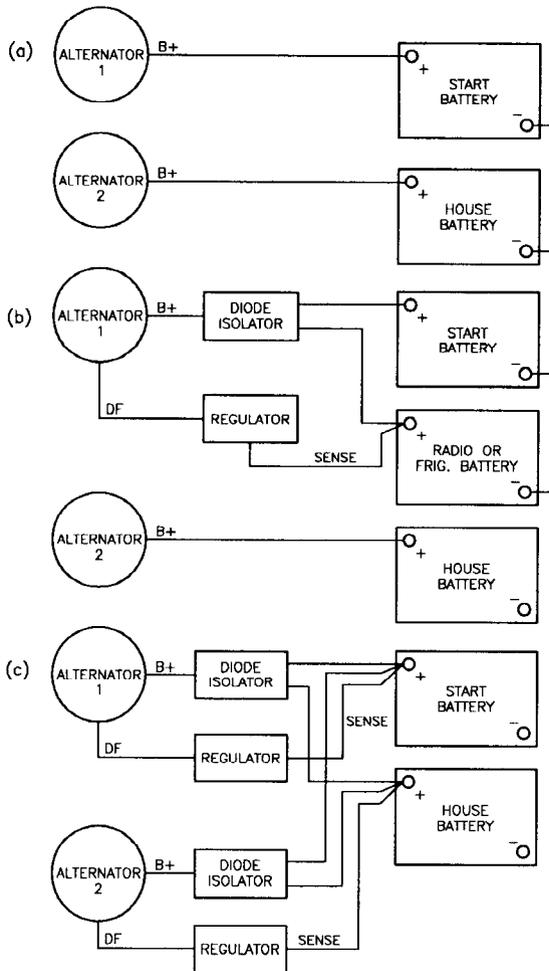


Figure 3-15. Two Alternator Charging Systems.

3.14. Diode Isolator Testing. On rare occasions a factory diode isolator may fail. This is normally due to an external event such as a surge or spike. The following tests can be carried out to verify operation:

- a. **Engine Operating.** Output terminal voltages should be identical. The input terminal should read approximately .75 volts higher if a non battery sensed regulator is being used. The diode system should not be used in these installations.
- b. **Engine Off.** Output terminal voltages should read the same as the service and starting batteries respectively. The input terminal from the alternator should be zero.
- c. **Ohmmeter Test.** Ensure all power is off before testing:
 - (1) Disconnect battery input and output cables.
 - (2) Set meter scale to x1.
 - (3) Connect red positive probe to input terminal.
 - (4) Connect black negative probe to output terminals 1 or 2.
 - (5) If good the meter will indicate minimal resistance.
 - (6) Reverse the probes, and repeat the test. The reading should indicate high resistance, or over range.

3.15. Recommendations. The following modifications should be performed on every vessel charging system:

- a. **Install Separate Negative Cable.** It is strongly recommended that a separate negative conductor of 10 mm² (6 B&S) be installed from the alternator case or negative terminal directly back to the battery negative. This by-passes the engine block, offers a good low resistance path and reduces stray currents through the block, which can cause pitting of bearings.
- b. **Replace Positive Cable.** Most installed positive cables are too small, especially if a fast charge device is installed. The cable size should be doubled. Ideally install a minimum of 10 mm². A problem is that besides having a maximum current going through it with fast charge devices or when heavily discharged batteries are recharged, the heat of the engine compartment also derates the current capacity of the cable. In most cases a significant volt drop develops across the cable under full output conditions.
- c. **Connectors.** Do not use the yellow insulated crimp ring connectors to terminate at the alternator, as they are not rated for the full alternator output current, use higher rated crimp connectors. Do not solder in place of crimping. If a connection is loose and develops a high resistance, the heat of the joint along with engine space temperatures will soon melt the connection. Additionally a large amount of vibration is transmitted through to the connections, and fatigue of soldered lugs and failures is a common failure cause.

- d. **Install Suppressors.** Many alternators do not have these fitted, so install them. Normally you will have noticed radio noise or interference on electronics equipment. A 2.2 micro farad is ideal, but even experimentation with a couple of automotive types is simple.
- e. **Separate Charging System.** If you can, separate the charging system from the starting circuit. Previous illustrations show how these various methods can be done, and in the long term, will considerably reduce problems and increase reliability.

Table 3-1. Charging System Fault Finding.

Symptom	Probable Fault	Corrective Action
Reduced Charging	Drive belt loose	Adjust to 10 mm
	Oil on belt	Clean belt
	Bad alternator connection	Repair connection
	Diode failure	Repair alternator
	Suppressor shorting	Replace suppressor
	Regulator faulty	Replace regulator
	Diode isolator fault	Replace diode
	Bad negative connection	Repair connection
	Solder connection fault	Resolder joints
	Undersized cables	Uprate cables
Over Charging	In-line ammeter fault	Repair connections
	Ammeter shunt	Repair connections
Over Charging	Regulator faulty	Replace regulator
	Sense wire off	Replace wire
No Charging	Drive belt loose	Tighten belt
	Drive belt broken	Replace belt
	Warning lamp failed	Replace lamp
	Auxiliary diode failure	Repair alternator
	Regulator faulty	Replace regulator
	Diode bridge failure	Repair alternator
	Brushes jammed	Clean brushgear
	Main winding failure	Repair alternator
	Rotor winding failure	Repair alternator
	Output connection off	Repair connection
Negative connection off	Repair connection	
Excess Water Use	Sulphated plates	Renew battery
	Overcharging	Replace regulator
	High ambient temp	Relocate batteries

3.16. Power Charging Systems. An alternative or addition to main propulsion energy charging systems is a dedicated engine powering an alternator, with possibly extra power take-offs for compressors, pumps or desalinator high pressure water pump. These can be either diesel or petrol driven. A traditional method has been the use of lay shafts, but they are often complicated and cause some difficulties. Systems are as follows:

- a. **Air Cooled Diesel.** Balmar in the United States have a unit driven by a 4 HP Yanmar diesel. Weighing only 65 lbs, it is fitted with 100 amp or greater alternator.
- b. **Water Cooled Diesel.** SeaFresh UK also have a multipurpose desalination system integrating charging and a reverse osmosis high pressure pump into a single unit. These systems also integrate hot water heating, and refrigeration compressor to utilise engine power economically.
- c. **Petrol.** MASE of Italy have a petrol powered portable unit that has an output of 50 amps DC at 14.2 volts. Weight is only 28 kg including an integral fuel tank:
 - (1) **Multihulls.** These are the perfect solution for multihulls where only an outboard is used for main propulsion and it utilises a common fuel type of petrol. It is a considerably cheaper and more efficient charging source than several solar panels, which can be reduced to a couple for a more balanced system.
 - (2) **Trailerable Yachts.** In the up to 26 foot small cruising yacht size, power is another problem area. Many vessels around this size only have outboards with limited charging and they provide a good DC power supply in these situations. In many cases the outboard is selected as a cheaper option to a small diesel, and as a result the engine space is vacant and such units can be easily installed.
- d. **Custom Units.** Units can be made to suit individual requirements, as some leading single handed yachts have used:
 - (1) On Australian Kay Cottee's "Blackmores First Lady" record breaking effort as the first woman solo around the world non-stop, a Yanmar air cooled engine was used. I was involved with the installation of a belt driven 80 Amp Bosch alternator with TWC regulator to improve the charging characteristic. This was to eliminate the use of the more fuel hungry main engine. As a back-up, the small diesel also had a small charging output off a flywheel generator.
 - (2) On Don McIntyres BOC vessel "Buttercup", a Yanmar water cooled diesel unit was installed with Bosch alternators and TWC regulators for a trouble free charging system.
 - (3) I have also used a 10 HP Kubota diesel, running an AC alternator, refrigeration compressor, air compressor and the DC charging alternator to reduce the required main engine run times.

ALTERNATIVE ENERGY SYSTEMS

4.0. Alternative Energy Charging Systems. More misconceptions exist about the capabilities of alternative energy systems on cruising yachts than virtually any other equipment. In most cases expectations are widely optimistic, and the realities in service at best disappointing. There are a few absolute truths that must be realised before embarking on what is large expenditure, and often a lot of engineering. These realities must be faced in spite of the philosophical factors and environmental awareness factors. The important factors are outlined below for consideration in that decision making process:

- a. **Secondary Power Sources.** Alternative energy charging systems should be integrated into the power system as a secondary power source where no further charging capacity can be derived from the engine alternator. In most cases alternative generation sources offer a significant reduction in dependence on engine based systems. As a battery on a poorly maintained vessel can lose as much as 14% of charge per month, they are ideal for battery maintenance in these situations. Alternative energy sources at the prevailing technology levels can only be considered as auxiliary charging sources. Ideally they should be used in conjunction with traditional methods and used as an integral component in the overall balanced power system.
- b. **Primary Power Sources.** There are many who for a variety of reasons choose to rely solely on one or several renewable power sources to supply electrical power. I have seen in a large number of cases a complete absence of understanding of basic electrical design factors. Planning systems requires considerably more stringent design criteria, a sailing philosophy that excludes a large number of electrical and electronics equipment, and not least a very disciplined lifestyle whilst cruising. If you want all the home comforts and technology, electric refrigeration, etc, then you are going to require a very large number of solar panels, wind generators, and probably water powered ones as well. You must realise, that the quoted output data is virtually always in absolutely ideal laboratory conditions, and in practice you will require a large factor above them to get a reasonable result. Cruising behaviour usually results in conditions that do not facilitate proper utilisation of the various methods as well. Last but not least, there are many who have had to adjust there cruising behaviour to one dominated by the search for both conserving battery power, and recharging them. Regrettably the natural forces that control alternative sources are far from predictable, and therein lies the other dominating factor.

4.1. Solar Systems. Solar energy concepts are not new, and date back to 1839 when the French scientist Becquerel discovered the photovoltaic phenomenon. The rapid developments in solar technology are generally a result of the space programs. Solar systems are the most commonly used alternative energy sources and offer a renewable and nearly maintenance free energy source. In many cases expectations are unrealistic with attempts made to make panels the primary charging system but there are a few practicalities to consider. At best they should be considered as an auxiliary charging source, although new advances may well change that over the next decade.

- a. **Theory.** The fundamental process of a solar cell is that when light falls on to a thin slice of silicon P & N substrate, a voltage is generated. This is called the photovoltaic principle. Cells consist of two layers, one positive, and one negative. When light energy photons enter the cell some are absorbed by the silicon atoms. This frees electrons in the negative layer which then flow through the external circuit (the battery) and back to the positive layer. When manufactured, the cells are electronically matched and connected into an array by connecting in series to form complete solar panels with typical peak power outputs of 16 volts.
- b. **Cell Types.** There a number of solar cell types and this is based on the cell material or structure used:
 - (1) **Mono-crystalline.** Pure, defect free silicon slices from a single grown crystal are used for these structures. The cell atomic structure is rigid and ordered and unlike amorphous cells cannot be easily bent. The cells are approximately 15%-20% efficient. The thin pure silicon wafers are etched within a caustic solution to create a textured surface. This textured surface consists of millions of four sided pyramids which act as efficient light traps reducing reflection losses. Panels are made by interconnecting 34-36 wafers onto a glass back and encapsulated.
 - (2) **Multi-crystalline.** These array types use wafers of silicon cut from a cast block. The multi-crystalline cell has better low light angle output levels and is now the most commonly used.
 - (3) **Amorphous Silicon.** Unlike crystalline cells these thin film panels have a loosely arranged atomic structure and are much less efficient. These type of cells are normally used in watches and calculators, and have lower outputs than other types. They do have the advantage that the cells can be applied to flexible plastic surfaces and as such flexible panels are made. Additionally they are capable of generating under low light conditions. I have heard of one enterprising yachtsman who always tries to park his stern under the marina floodlights, so that he gets some trickle charging at night. Crystalline cells won't do this. The big disadvantage is that power outputs are nearly a quarter of crystalline cells of the same size.

c. **Construction.** Cell arrays are normally laminated under Ethylene Vinyl Acetate (EVA). Anti-reflection coatings using titanium dioxide are used, and some are characterised by a blue colouring. This is also to increase gathering of light at the blue end of the light spectrum. Panels are constructed to be moisture and ultra violet resistant. Glass is tempered and toughened and glass surfaces may be textured to reduce reflection, increase surface areas and improve light gathering in low angle lighting conditions. Solar arrays often utilise front and rear interconnections to improve faulty cell redundancy.

d. **Ratings.** Efficiency is at an optimum when a solar panel is angled directly towards the sun and manufacturers rate panels at specific test standards. The most effective panels are rigid units while the flexible units have significantly lower outputs:

(1) **Output Specifications.** These are normally quoted to a standard, typically 1000W/m sq at 25° C cell temperature and spectrum of 1.5 air mass. The level of irradiance is measured in watts per square metre. The irradiance value is multiplied by time duration to give wathours per square metre per day.

e. **Efficiency.** Location and seasonal factors affect the amount of energy available. Cells are approximately 15% efficient and start producing a voltage as low as 5% of full sunlight value:

(1) **Solar Angles.** Solar angles are important to the efficiency of panels. With the sun at 90° overhead, panels give 100% output. When angled at 75°, the output falls to approximately 95%, at 50° output falls to 75%, and a lower light angle of 30° gives a reduction to 50%.

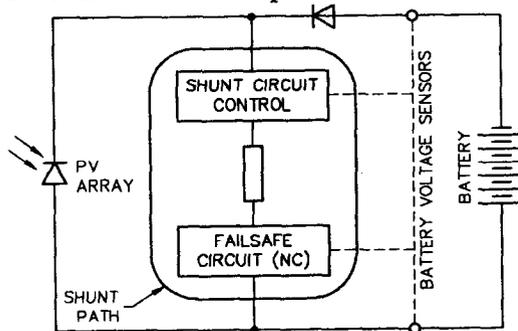
(2) **Average Seasonal Hours.** Table 4-1 shows typical seasonal hours and yearly averages based on solar array tilted towards the sun at an angle equal to latitude of the location +15°.

Table 4-1. Peak Solar Level Table.

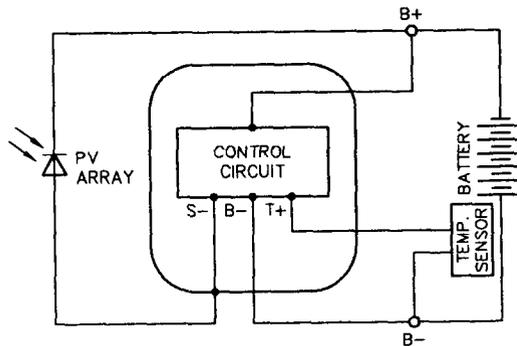
Location	Winter Hours	Summer Hours	Average
EAST AUST	4.5	5.5	5.0
NORTH AUST	4.5	6.0	5.3
PACIFIC	4.5	6.0	5.3
CARIBBEAN	5.5	5.5	5.5
NORTH EUROPE	1.5	4.0	2.7
SOUTH ENGLAND	0.6	5.0	2.8
SOUTH FRANCE	2.5	7.5	5.0
GREECE	2.4	7.4	4.9
AZORES	2.2	6.0	4.1
CALIFORNIA	4.0	5.0	4.5
MIAMI	3.6	6.2	4.9
SE ASIA	4.0	5.5	4.7
CAPETOWN	4.0	5.0	4.5
RED SEA	6.0	6.5	6.3
INDIAN OCEAN	5.0	5.5	5.3

f. **Panel Regulation.** In any panel over a small 12-15 watt unit, a regulator is required to restrict the voltage to a safe level. It is not uncommon to have voltage levels rise to 15-16 volts, and the boiling dry of batteries over any extended and unsupervised period. There are solar control devices in use which must not be confused. One is simply to limit voltage to safe levels and the other device, called a linear current booster increases power for certain conditions:

- (1) **Regulators.** The regulator functions simply to limit panel output voltage to a safe level and prevent damage to a battery. Units may be simple and limit voltage to 13.8 volts, the maximum float level, dissipating heat through a heat sink. More sophisticated units should be used to get the most from the panel. These units incorporate an automatic boost level of 14.2 volts and a float setting of 13.8. The regulator float charges the battery until a lower limit of approximately 12.5 volts is reached before switching to boost. The units normally eliminate the need for an additional blocking diode. Check the manufacturer's data sheet first. Some regulators also have temperature compensation installed and must be installed adjacent to the batteries.
- (2) **Linear Current Booster.** These electronic devices boost current from the module. Primarily they are designed to prevent stalling of permanent magnet motors. Effectively they are constant current devices. Units are primarily used in applications where panels directly supply a load. They are not useful on boats where the panel is used to charge a battery.



(a) SHUNT CONTROL REGULATOR (SOLAREX)



(b) TYPICAL SOLAR REGULATOR

Figure 4-1. Typical Solar Regulator Systems.

g. Diodes. Most panels have diodes installed and the following points on the use of them are described. There is a rather flawed argument that the use of a diode reduces charging voltage. This is true, as a diode reduces voltage by approximately 0.75 V, but if you are installing a couple of three amp panels which is typical, you will require a regulator to reduce the voltage to avoid overcharging and damaging your batteries. If the regulator is a good unit the control will float between 14.5 and 13.8 volts, so this voltage drop will not be a problem. If the regulator has the appropriate reverse current protection such as a diode, then the panel installed unit can be removed to increase the input voltage to the regulator which gives a marginally higher output. If you are not going to regulate the solar supply, then failure to install or leave the diode installed will result in a flat battery overnight. There are two functional uses of diodes which are as follows:

- (1) By-pass Diodes.** By-pass diodes are normally factory installed within solar module junction boxes. By-pass diodes are used to reduce power losses that might occur if a module within the array is partially shaded. For 12 volt systems these offer sufficient circuit protection without the use of a blocking diode. In 24 volt systems with 2 or more modules connected in series, the solar modules should be connected in individual series circuits. To obtain the required total array current the circuits should then be paralleled. If one module of a parallel array is shaded, reverse current flow may occur.
 - (2) Blocking Diodes.** Blocking diodes are often connected in series with solar panel output to prevent discharge of the battery back to the array at night, but not all manufacturers install them as standard. If the panels do not have a diode then a diode rated to 1.5 times the maximum output (5 amps) and should be installed at the regulator input. Most solar regulators will often have the diode incorporated and generally all panels with a by-pass diode installed in the connection box do not require any further diode.
- h. Charging System Interaction.** There is often an interaction between solar panels and alternator charging regulators, when they are left on during engine charging periods. In many cases, solar panels are not regulated, and it is quite common to see a voltage of up to 16 volts across the battery. Notwithstanding the damage to batteries that can occur, when an alternator regulator senses this high voltage level, it simply registers this as a fully charged battery, and as a result the alternator does not charge the battery, or at a very minimal rate. When installing panels and regulators, ensure the following features are installed with them:
- (1) Isolation Switch.** Always ensure that an isolation switch is installed on the incoming line to the panel so that it can be switched out of circuit.
 - (2) Regulator By-pass Switch.** Always install a switch that can by pass the regulator and apply full panel output to the battery. This will make periodic equalisation easier and charging a dead battery more efficient.

i. **Sight Selection.** Solar panel rating selection is largely dependent on the physical space available for installation. The following options are the most common and most efficient. In all cases it is essential to ensure that panels are not shadowed by sails, spars or any other equipment. Ideally panels should be angled towards the sun if at all possible, but in practical terms this is not possible on a cruising yacht. Generally panels mounted flat will offer the best compromise, which is why the stern arch configuration is becoming so popular:

- (1) **Coach House.** Panels ideally are mounted on coach-house tops, but depending on which tack, one panel will often be shaded and the other illuminated.
- (2) **Stern Brackets.** This arrangement is really only suitable for a single panel, and is usually designed to allow adjustment of the panel angle.
- (3) **Stern Arches.** This is becoming the most popular method and allows the easy installation of at least two 3 amp panels which are clear and unobstructed.
- (4) **Pushpit Rails.** This arrangement uses two panels mounted on swing up brackets on each side of the vessel, normally close to and on the pushpit rails. Depending on which tack, or direction of sun, the panels can be put into service, and folded down if not used.
- (5) **Multihulls.** The much greater deck area of a multihull, and the near flat sailing attitude make sight selection much easier, and increased efficiency. In most cases, a large coach house can be utilised, and on trimarans, arrays can be mounted at the outer hulls well clear of shadowing.

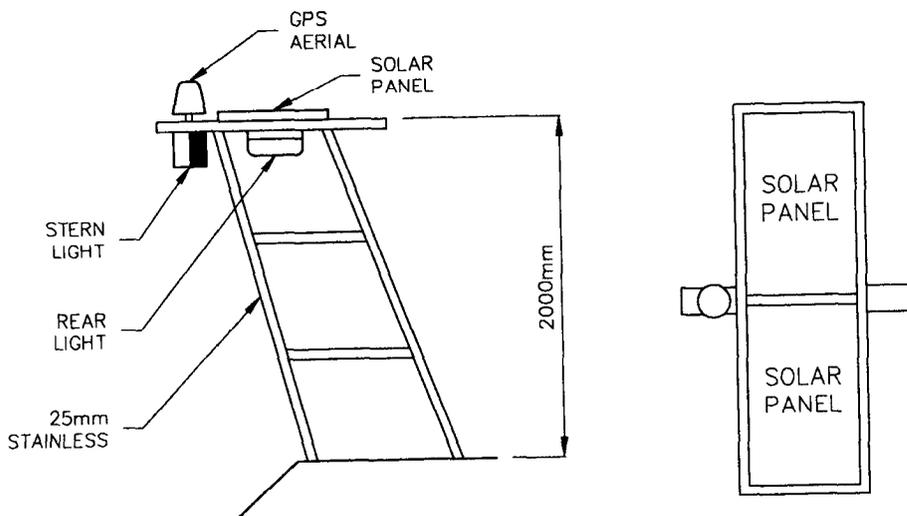


Figure 4-2. Stern Arch Arrangement.

j. Installation. Solar panels are manufactured in either rigid or flexible form. Cabling should be properly rated to avoid voltage drop, and (15 Amp) 2.5 mm² cable is a minimum to cope with two 65 watt panels. As cable is external, use tinned copper marine cable. Most panels have weather-proof connection boxes and connections should be simply twisted and terminated in terminals. Do not use connectors or solder the wire ends. Manufacturers also specify grounding of array or module metallic frames. I have heard concerns over vessels that have automatic bilge pump arrangements with a solar panel charging the battery. If the pump cable develops a fault, that once the battery is flat a serious electrolytic corrosion problem may develop and corrode skin fittings and hull as a voltage is being applied directly to them. Although theoretically possible, I have never heard of this occurring and it would be extremely rare. If it is a concern, operate the bilge pump off the non-charging battery.

(1) **Panel Safety.** Cover solar panels to prevent a voltage being generated during installation or removal so that accidental short circuiting of terminals or cables cannot occur.

(2) **Mounting.** Each panel should be securely mounted and able to withstand mechanical loads. Ideally they should be orientated to provide unrestricted sunlight from 9 to 3 pm solar time.

(3) **Stand-offs.** Allow sufficient ventilation under the panel. Most panels in frames have sufficient clearance incorporated into them. Excessive heat levels will reduce output and damage cells.

k. Maintenance. Maintenance requirements of solar panels are minimal. The essential tasks are as follows:

(1) **Cleaning.** Panels should be cleaned periodically to remove salt deposits, dirt and seagull droppings. Use water and a soft cloth or sponge. Mild, non abrasive cleaners may be used, do not use any scouring powders or similar materials.

(2) **Connections.** Check terminal box connections are secure and dry. Fill the box with silicon compound.

l. Fault Finding. Faults are normally catastrophic mechanical damage. A single cell failure will not seriously reduce performance as multiple cell interconnections provide some redundancy. Reliability is very high and manufacturers give 10 year warranties to support this. Faults can be virtually eliminated by proper mounting and regular maintenance. As with all electrical systems, the most common faults are cable connections. The following checks should be carried out if charging is not occurring:

(1) Check regulator output for rated voltage, typically 13.2 V DC.

(2) Check regulator input, voltage will be typically 14 volts plus. Disconnected from battery it can be up to 17-18 volts.

(3) Check panel junction boxes for moisture or corroded connections.

4.2. Wind Charging Systems. Wind generators are the second most used alternative source. There are like all charging systems, important factors to consider when deciding whether to install a unit as part of a balanced power system. The following chapter outlines the various factors to consider:

- a. Cruising Patterns.** Wind generators appear more effective in some areas than others. In the Caribbean they are very effective, and in the Mediterranean, solar power is considered more efficient. If you sail downwind following the trades then they are not effective, as the apparent wind speed is reduced, with a subsequent reduction in charging capability. If your cruising lifestyle takes you primarily to sheltered anchorages then they may not be an economical or practical proposition.
- b. Generator Types.** Essentially a wind generator is either a DC generator or alternator driven by a propeller. In the USA the trend is for two or three bladed units which give relatively good low wind speed outputs with the Windbugger appearing to be the most popular. The UK/European trend is for smaller diameter multi-bladed units which are designed to operate at and withstand greater wind speeds. These units incorporate a heavy hub that acts as a flywheel to maintain blade inertia.
- c. Generator Operation.** Many units have a permanent magnet rotor, with up to 12 poles. A three phase alternating current is generated and rectified to DC similar to engine driven alternators. The Rutland 910 unit circuit is illustrated below.

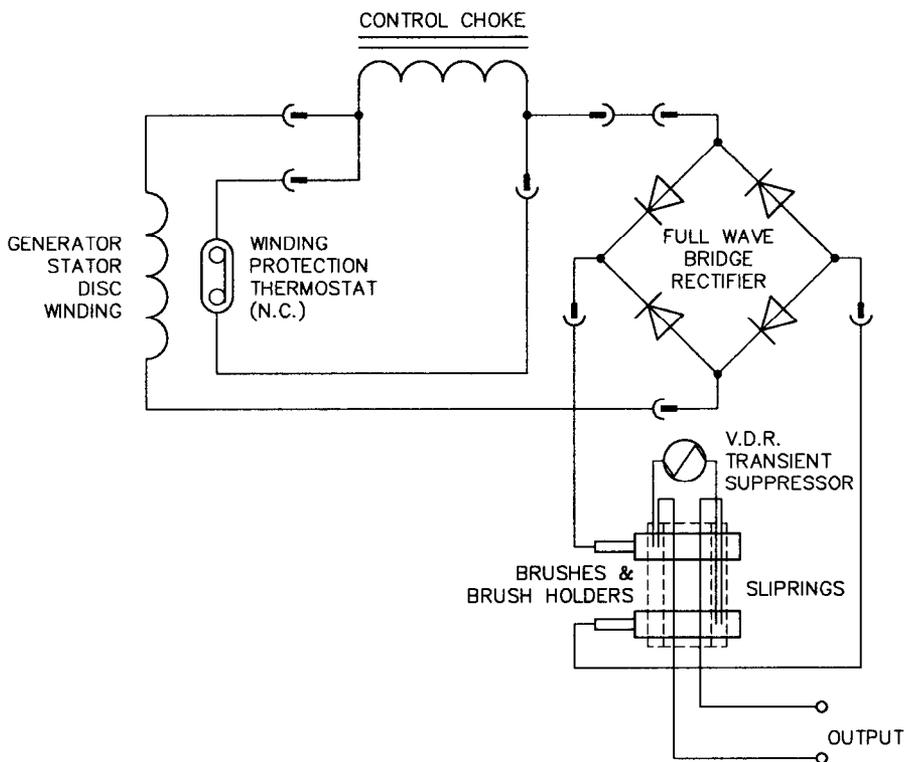


Figure 4-3. Rutland Wind Generator Circuit

- d. **Ratings.** The average wind generator typically produces anything from 1 amp to 10 amps maximum. Ratings curves are always a function of wind speed and are quoted at rated output voltages. Typical ratings are given in Table 4-2 for a number of generators.

Table 4-2. Wind Generator Output Table.

Make/Model	Output Current	Wind Speed
Aerogen 3	1.0 Amps	10 Knots
	2.0	13
	3.0	18
	6.0	25
	10.0	35
Rutland 910	2.0	15
	3.0	18
	5.0	27
	6.0	35
	8.0	45
LVM 50	0.5	7
	1.0	11
	2.0	24
	7.0	34
AMPAIR	1.0	10
	2.0	13
	3.0	18
	6.0	25
	7.0	45

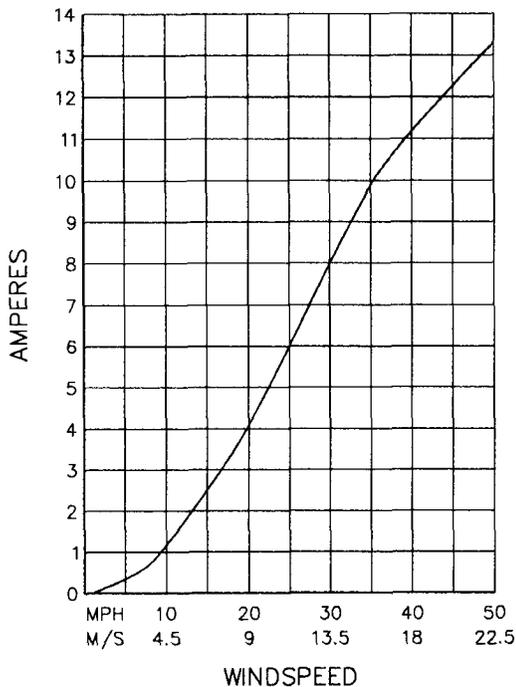


Figure 4-4. Wind Generator Performance Curve

e. **Charging Regulation.** There are a number of features incorporated into wind generators to protect batteries and generators. These are as follows:

- (1) **Regulators.** A regulator is required to both limit normal charging to a safe level and to limit output at high wind speeds. Normally a shunt regulator is preferred over a normal solar panel regulator as they are more suited to constant loads. Shunt regulators divert excess current to a resistor which functions as a heater and dissipates heat through a heat sink. If series regulators are used, a power zener diode should be installed to provide some load when the battery is fully charged. Twelve volt systems should use an 18-volt zener diode. The zener must be rated for at least half rated generator output.
- (2) **Chokes.** Some units incorporate a choke to limit the charge produced at high wind speeds.
- (3) **Winding Thermostats.** A number of generators incorporate a winding embedded thermostat which opens in overload conditions. This operates when the winding overheats.
- (4) **Transient Suppressors.** These suppressors are installed to minimise the effects of intermittent spikes being impressed on the charging system, which would otherwise damage the rectifier and onboard electronics. The suppressor is usually a Voltage Dependant Resistor (VDR).

f. **Installation.** Selection is largely dependent on available mounting locations. Arrangements vary, some are mounted on the front of the mast, and others are made hoistable.

- (1) **Stern Posts.** The ideal arrangement is on a stern post which keeps the blades clear of crew and benefits from air coming off the mainsail. One of the major complaints is that under load the wind generator creates vibration. It is essential that the post be as thick sectioned as possible and supported. Usually this extra support is on the pushpit and some install stainless steel wire stays.
- (2) **Mountings.** Mountings can also be cushioned with rubber blocks or similar material to reduce the transmission of vibrations. Rutland chargers have a tie bar modification that strengthens the blades and prevents excessive blade deformation under load and the increased vibration that occurs. Newer models have improved blade design and strength that prevents blade breakage.

- g. Fault Finding.** Always secure the turbine blades when installing, servicing or fault finding a wind generator. The following performance tests should be carried out:
- (1) If no ammeter is installed on the main switchboard install an ammeter in line and check the charging current level. If there is no output then check the system according to the manufacturers instructions.
 - (2) If there is no output and the generator has brushes, then check that they are free to move and are not stuck. Many generators do not have brushes and commutators, but a set of sliprings are installed with brushes to transfer power from the rotating generator down through the post to the battery circuit. They can jam and on rare occasions cause loss of power.
 - (3) Some generators have a winding imbedded thermostat. Check with an ohmmeter that it is not permanently open circuited. If it is open circuited the generator will not charge. The thermostat will open in high wind charging conditions. If the thermostat has not closed after these conditions and the generator case is cold, the thermostat is defective. Regrettably there is nothing that can be done to repair it unless a new winding is installed. To get the generator back into service, connect a bridge across the thermostat terminals. Remember that there will be no protection, and in high wind and heavy charging conditions that the winding may burn out.
 - (4) Excess vibration may be caused by bearing wear. If the unit is a few years old then renew the bearings. Vibration can also be caused by damage to one or more blades, and these should be carefully examined for damage that may be causing imbalances.
 - (5) Check the rectifier to ensure that it is not open or short circuited.
 - (6) If the generator output is correct, check the regulator is not malfunctioning. The voltage input may be in the range 14-18 volts, and the output approximately 13-14 volts.
 - (7) Ensure all electrical connections are secure and in good condition.

4.3. Prop Shaft Charging Systems. Prop shaft generator systems are either traditional alternators with prop shaft gearing to achieve rated output, or alternators wound to achieve low speed outputs. Systems are either for use as an extra power source whilst under engine propulsion, which is not an economic proposition, or used to take advantage of the free-wheeling propeller under sail. The following points must be considered:

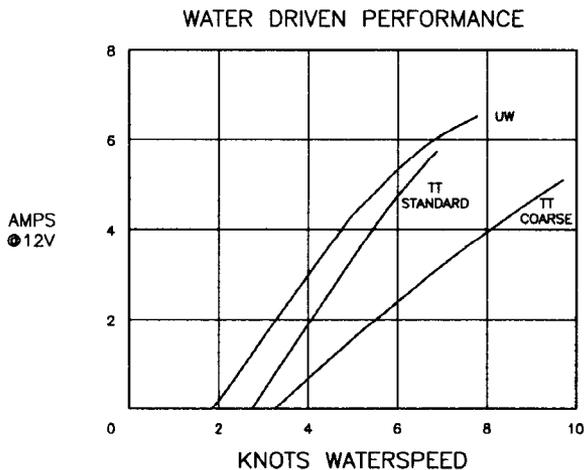
- a. **Cruising Patterns.** One important point to remember about the viability of these units is your own cruising pattern. Consider that only about one quarter to one third of your time is spent passage making, and therefore the shaft alternator is used for a very limited period.
- b. **Drag.** Under any load, the alternator will brake the shaft by slowing shaft rotation, causing additional drag and a reduction in vessel speed. On a lightweight vessel this is normally unacceptable and can be as high as half a knot. On steel or other heavy displacement vessels, the inertia of the vessel will generally result in minimal drag effect. For such cruising yachts, they are a useful proposition. With an increasing number of yachts opting for both two and three bladed folding props, shaft alternators may be rarely used.
- c. **Output.** The maximum output will generally be in the region of 5-10 amps. The Lucas unit has a maximum output of 12 amps, with an approximate output of 1 amp per knot. Cut-in speed is 600 rev/min and requires a shaft pulley ratio of 5:1. One major fear has been gearbox damage due to improper lubrication while freewheeling but many major gearbox manufacturers have dispelled this fear.

4.4. Water Charging Systems. Water based charging systems come in two configurations:

- a. **Towed Turbine Generator.** The towed turbine water generator is essentially a slow speed alternator with the drive shaft mechanically connected to a braided rope and turbine assembly. When streamed off the stern, the turbine turns and rotates the alternator. Typical output is approximately 6 amps. The trail rope is typically around 30 metres long:
 - (1) **Drag.** Typical drag speed reduction is around half a knot. The trail generator, like the old fashioned trailing log are reliable, and extra hungry denizens rarely eat the turbine.
 - (2) **Turbine Skipping.** One problem is that the turbine tends to skip out of the water across wave heights at speeds over 6 knots, in less than normal sea states. The Ampair units have two turbine types, one for speeds up to 7 knots, and another coarse pitch turbine for higher speeds to minimise this problem. There are a variety of methods to reduce skipping, which include adding sinker weights to the turbine, increasing the tow line length and increasing the tow line diameter.

b. **Submerged Generator.** These units comprise a forward facing three bladed propeller that drives a permanent magnet alternator. The propeller is mounted at the end of a tubular arm at a depth of approximately 1 metre. As a water driven power source they are a good option, being easy to lift and service. Maximum output is approximately 8 amps.

- (1) **Drag.** The drag on a submerged generator is approximately double that of a towed generator.
- (2) **Physical Characteristics.** As the electrical alternator is underwater certain constructional features are employed. The generator housing has double seals, as do the cable glands. The alternator body is filled with hydraulic fluid to equalise external pressures when fully extended in the water. The reservoir is fitted to allow for oil expansion and contraction.
- (3) **Mounting Locations.** Generators can be mounted either directly on the transom or on the taffrails.



UW = UNDERWATER GENERATOR
 TT STANDARD = TOWED TURBINE - STANDARD PITCH
 TT COARSE = TOWED TURBINE - COARSE PITCH

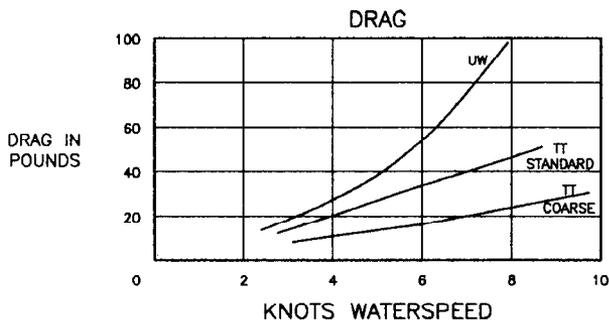


Figure 4-5. Water Generation System Characteristics.

AC MAINS CHARGERS

5.1
use

5.0. Battery Mains Chargers. Mains chargers are only used as a primary charging source in large vessels with AC generators in continual service. Many vessels have had batteries ruined by poor quality chargers due to a marginal overcharge voltage level. In reality, mains chargers are not a principal charging source on a cruising yacht, and a relatively small output automatic charger of approximately 10 - 15 amps will meet the normal requirements whilst alongside. The basic principals of most basic battery chargers is as follows:

- a. Transformation.** The mains voltage, either 230 or 110 volts AC is applied to a transformer. The transformer steps down the voltage to a low level, typically around 15/30 volts depending on the output level.
- b. Rectification.** The low level AC voltage is then rectified by a full wave bridge rectifier similar to that in an alternator. The rectifier outputs a voltage of around 13.8/27.6 volts, which is the normal float voltage level.
- c. Regulation.** Many basic chargers do not have any output regulation. Chargers that do have regulation are normally those that use control systems to control output voltage levels. These sensing circuits automatically limit charge voltages to nominal levels and reduce to float values when the predetermined full charge condition is reached.
- d. Protection.** Chargers have a range of protective devices that range from a simple AC input fuse to the many features that are described as follows:
 - (1) Thermal Overload.** These devices are normally mounted on the transformer, or rectifier. When a predetermined high temperature is reached, the device opens and prevents further charging until the components cool down.
 - (2) Input Protection.** This is either a circuit breaker or fuse that protects the AC input against overload and short circuit on the primary side of the transformer.
 - (3) Reverse Polarity Fuse.** A fuse is incorporated to protect circuits against accidental polarity reversal of output leads.
 - (4) Current Limiting.** Limiting circuits are used to prevent excessive current outputs, or to maintain current levels at a specific level.
 - (5) Short Circuit Protection.** This is usually a fuse that protects output circuits against high current short circuit damage.
- d. Interference Suppression.** Most chargers have an output voltage ripple superimposed on the DC. This is overcome by the use of chokes and capacitors across the output. This ripple can affect electronics and cause data corruption on navigation equipment.

5.1. Charger Types. There are a number of charger types and techniques in use as follows:

- a. **Constant Potential Chargers.** Chargers operate at a fixed voltage. The charge current decreases as the battery voltage reaches the preset charging voltage. Batteries can sustain damage if unsupervised as electrolytes evaporate, and gas formation can be excessive. Additionally such chargers are susceptible to mains input voltage variations. If left unattended, the voltage setting must be below 13.5 volts, or batteries will be ruined through overcharging.
- b. **Constant Current, Constant Voltage.** This charging technique entails the application of a constant current to charge the battery. When the gassing voltage is reached, typically in the range 14.4 to 14.6 volts corrected for temperature, the charge current is reduced to a float charge constant voltage condition.
- c. **Cycle Chargers.** TWC of Sweden have a charger that has the same charging characteristics as the alternator control regulator. One unusual feature of this unit is that if the boat is left unattended for more than ten days, the charger automatically partially discharges the battery bank by 25% and recharges it to "work" it. Additionally the unit commences each charge cycle phase with a current surge that has the same effect as an equalising charge.

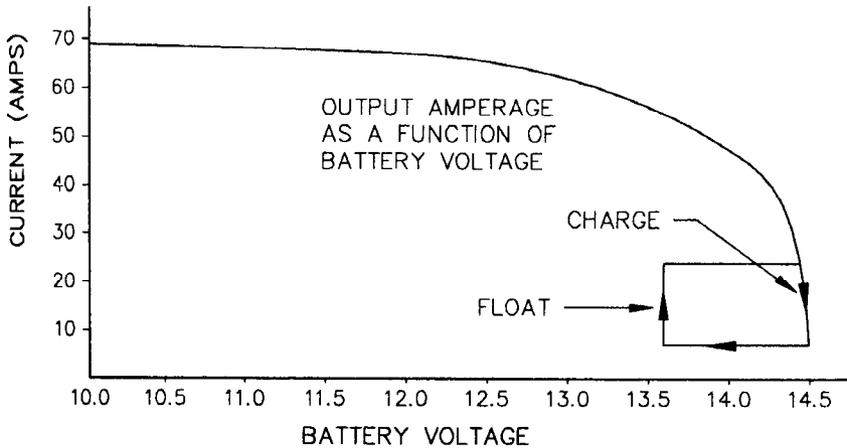


Figure 5-1. NEWMAR Universal Charger Characteristics.

- d. **Ferro Resonant Chargers.** These chargers use a ferro resonant transformer which have two secondary windings. One of the windings is connected to a capacitor, and they resonate at a specific frequency. Variations in the input voltage cause an imbalance, and the transformer corrects this to maintain a stable output. These chargers have a tapered charge characteristic. As the battery terminal voltage rises, the charge current decreases. Control of these chargers is usually through a sensing circuit that switches the charger off when the nominal voltage level is reached, typically around 15% to 20% of charger nominal rating.

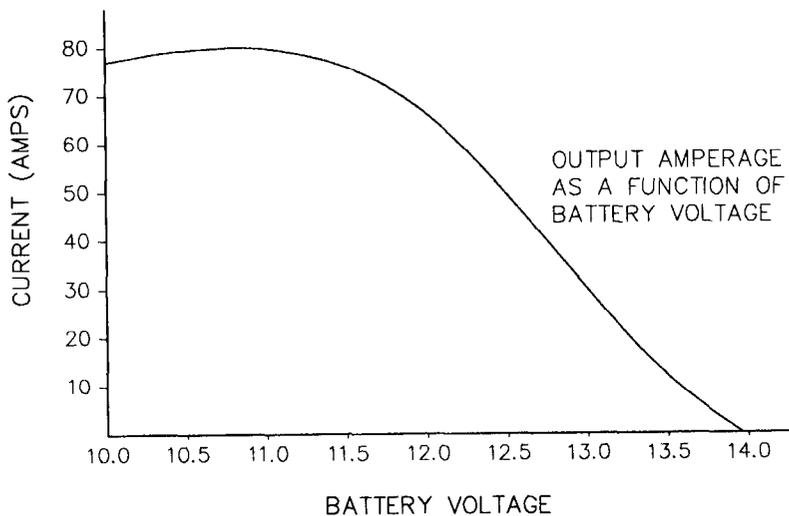


Figure 5-2. NEWMAR Ferro Resonant Charger Characteristics.

- e. **Switch-Mode Chargers.** Compact switch-mode chargers are becoming increasingly popular due to their compact size and low weights. These charger types convert the input line frequency from 50 to 150,000 hertz which reduces the size of transformers and chokes used in conventional chargers. An advantage of these chargers is that line input and output are effectively isolated eliminating the effects of surges and spikes. These chargers are my own choice, and units such as those from LEAB of Sweden are technically very advanced. The chargers are battery sensed, temperature compensated, have integral digital voltmeter and ammeters, and are physically very compact. The illustration below shows the principal of operation and the various waveform conversions from the AC input to a stable DC output.

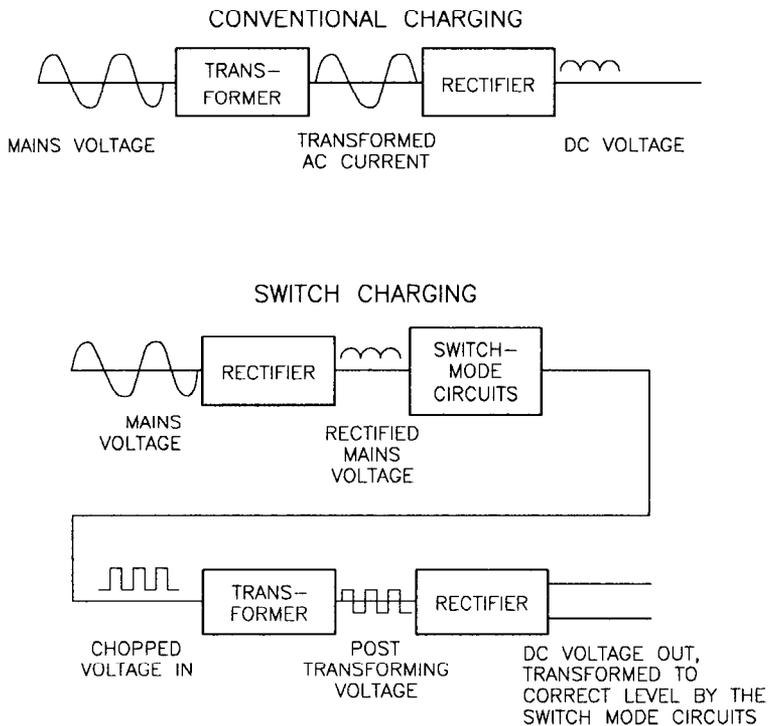
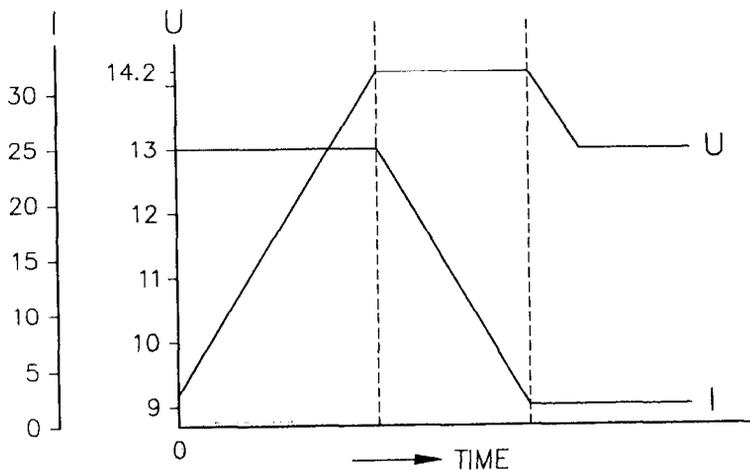


Figure 5-3. LEAB Switch Mode Charger System.

- f. **Automatic Chargers.** This term covers a large range of electronic controlled charging systems. These include chargers that have SCR or Triac control, a combination of current and voltage settings, with appropriate sensing systems and control systems, as well as overvoltage and overcurrent protection. The ideal charger characteristic is one that can deliver the boost charge required and automatic dropping to float charge levels so that overcharging does not occur.

5.2. Charger Installation. Chargers should be mounted in a dry and well ventilated area. The following precautions should be undertaken when using chargers:

- a. Always switch off battery charger during engine starting if connected to the starting battery.
- b. Mains connection should be an industrial grade outlet in engine areas or normal outlet in dry areas.
- c. The metal case of any charger must be properly grounded to the AC ground.
- d. Clips or permanent fasteners should be used on cables if the charger is permanently installed to prevent cables from moving.
- e. Switch off the charger before connecting or disconnecting cables from battery.
- f. Do not operate a large inverter off a battery with a charger still operating. The large load will overload the charger and may cause damage to circuitry.



I = CHARGING CURRENT (AMPS)
 U = CHARGING VOLTAGE (VOLTS)
 13V = MAINTENANCE /FLOAT VOLTAGE

Figure 5-4. Automatic Charger Characteristics.

DC SYSTEMS INSTALLATION.

6.0. DC Systems. This chapter encompasses the selection and correct installation of cables, terminations and circuit protective devices. The following points should be noted:

- a. **Failure Rates.** A significant proportion of vessel failures, estimated at up to 80%, are directly attributable to incorrectly selected or installed cables, or improper connections and terminations. Most minor failures can be eliminated by using simple accepted practices. Unfortunately the common attitude is to still treat vessel low voltage systems similar to automotive installations and the high failure rates on cruising vessels reflect this attitude.
- b. **Fire Risks.** Exposure of DC systems to water is still capable of causing fire, shock and catastrophic damage.
- c. **Ratings.** All installed equipment used in DC electrical systems must be rated for DC, not AC.

6.1. DC Systems Voltages. System voltages vary and all have their merits. The three main system voltages are as follows:

- a. **Voltages.** The three principal voltages are 12, 24 and 32 volts, the latter being less common these days:
 - (1) **12 Volt Systems.** The 12 volt system is the most common. This is due to the large range of equipment available that can be directly connected. The majority of electronic equipment are available to run on either 12 or 24 volt. It is now possible to purchase toasters, washing machines, and virtually any appliances in 12 volts.
 - (2) **24 Volt Systems.** This system is prevalent, especially in commercial applications. It has the advantage of lower physical equipment sizes, cabling and control gear. Additionally voltage drops are not as critical. As equipment is commonly 12 volts a DC-DC converter must be used to step down to 12 volt equipment. Although complicating the system a little this does offer isolation of sensitive electronics equipment from the surge and spike prone power system.
 - (3) **32 Volt Systems.** This voltage system is not that common now, and appears to be mainly confined to some American vessels. It has a major disadvantage in that there is very little voltage compatible equipment and conversion is expensive.
- b. **Mixed Voltage Systems.** It is quite common to see vessels having both 12 and 24 volt systems in use. Effectively they should be treated as two entirely separate entities with no interconnection electrically. This will mean two alternators and two battery banks. The merits of 24 volts for heavy current consumption equipment such as invertors and windlasses is obvious as cable half the size and weight can be used. In many cases electronics will be able to operate on 24 volts without modification.

6.2. DC Voltage Conversion. In many vessels, a mix of voltages requires the use of DC converters to step down from 24 to 12 volts. There are a number of technical points that must be considered when selecting and installing converters:

- a. **Output Isolation.** Converters may either galvanically isolated or only isolated in the positive conversion circuit. Galvanically isolated units will totally isolate input and output providing protection to connected loads, and these are preferable.
- b. **Output Stability.** Good quality converters have a stabilised output of around 13.6 volts. They should also have radio interference suppression. Stability is typically about 1% between line and load at rated output voltage.
- c. **Idle Current Consumption.** Typical power consumption of a converter without a load connected is approximately 40 to 50 milliamps, so there will always be a battery drain. The converter should ideally have an isolation switch on the input side.
- d. **Peak Power Output.** Converters are able to withstand short surge current. Normally a 50% over current can be applied for intermittent surges, and approximately 70% for a very short duration of up to 30 seconds for peak loads. Some high power units can withstand peak overloads of 200% for up to 30 seconds.
- e. **Output Ratings.** Output ratings vary but I usually install one rated at approximately 15 Amps continuous. Duty cycle ratings are also applicable to converters. Intermittent overloads can only be sustained on a cycle of 20 minutes every hour, and peaks for a 30 to 60 seconds per hour. Failure to observe these duty cycles will result in a burnt out converter.
- f. **Output Derating.** Converters like most electrical equipment is designed to provide an output at a specific temperature range, typically 0 - 40°C. At 50°C, converters should be derated to 50%.
- g. **Installation.** Good ventilation is essential. Converters should be mounted vertically so that fins are also vertical to facilitate convection. Sufficient clearance must be allowed between top and bottom so that air flow is not obstructed.
- h. **Protection.** Most converters are installed with automatic thermal shutdown, short circuit fuse protection, current limiting and reverse polarity protection.

6.3. Wiring Configurations. The majority of cruising yachts have a centralised distribution system based at a single switch panel, while larger vessels, and more increasingly smaller ones are using a system of sub-panels. There are two basic wiring configurations in use on vessels regardless of the system, and these are described as follows:

- a. Two Wire Insulated Return Systems.** This type of configuration is the preferred system, and that includes the various classification societies. All steel and alloy vessels must be of the 2 wire insulated return. This configuration has no part of the circuit, in particular the negative, connected to any ground or equipment. The system is totally isolated, and this includes engine sensors, starter motors and alternators. This system must be installed on steel and alloy vessels.

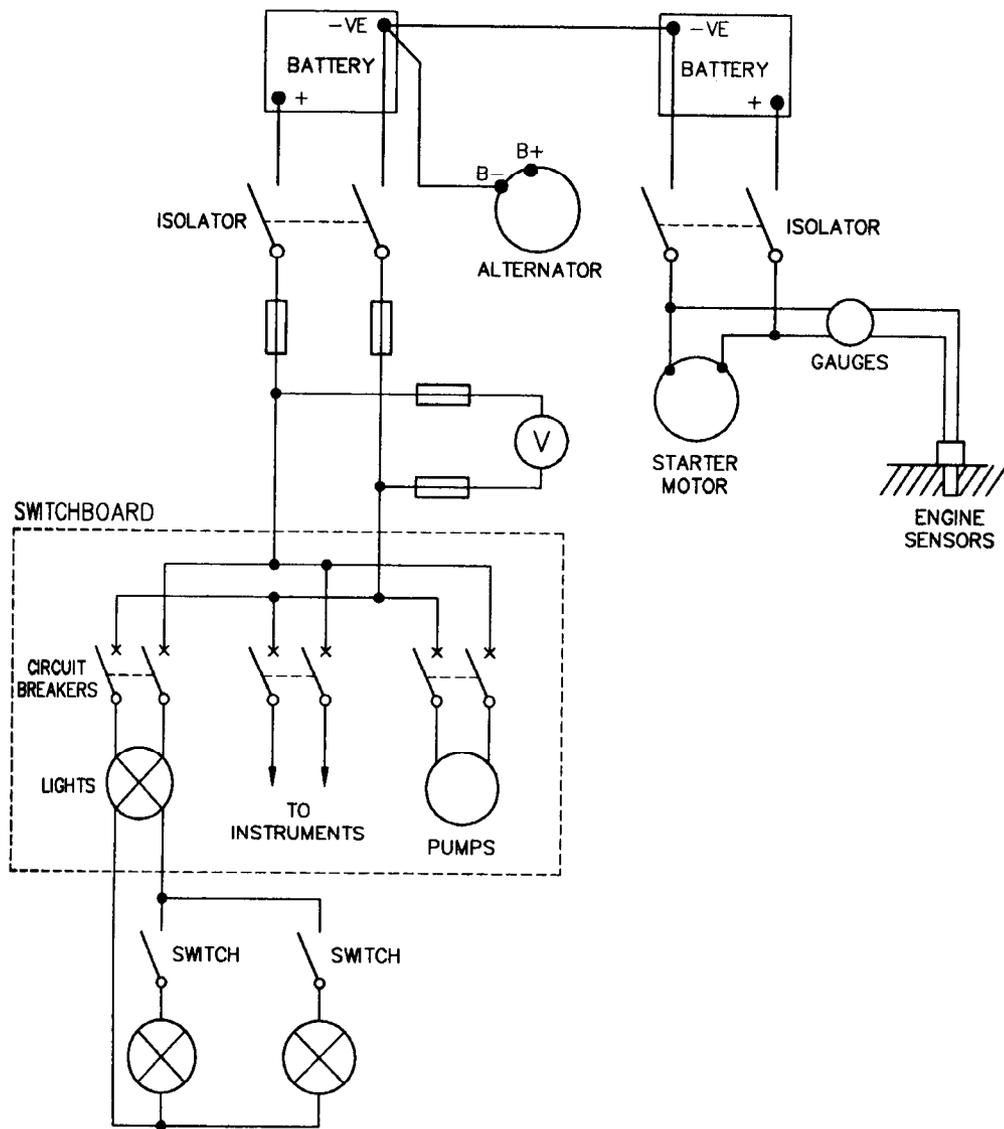


Figure 6-1. Insulated 2 Wire Return Systems.

- b. **Insulated Return One Pole Grounded.** Insulated return and one pole grounded (negative) is the other alternative. This effectively grounds the negative and is quite common where the negative is using the engine block as a ground. This is often by default rather than due to any design considerations, and is much cheaper to implement. In GRP and timber vessels this system is common and suitable but in steel and alloy vessels this poses very considerable corrosion risks.

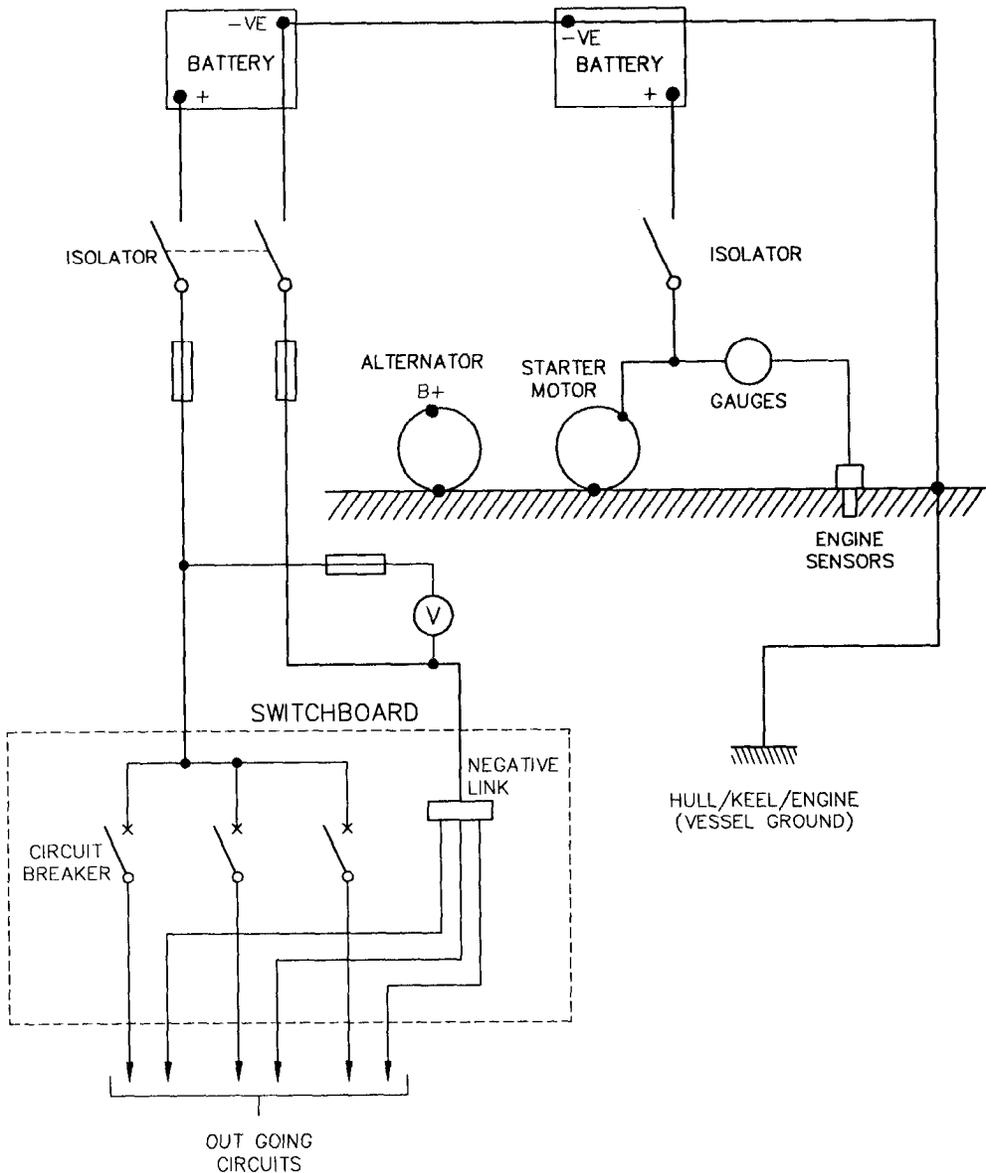


Figure 6-2. Insulated 1 Pole Return Systems.

c. **Distributed Systems.** These systems are typically broken down into a system of sub-panels, and it is becoming increasingly preferable with the growth in installed equipment. There are a number of significant advantages over a centralised system which include the separation of potentially interactive equipment such as pumps and electronics which causes radio frequency interference (RFI). Separation enables a reduction in the number of cables radiating throughout the vessel from the main panel to areas of equipment concentration, which is also a cause of RFI and considerably greater quantity of cable. Most distributed systems run all the sub-circuits from the central panel, with each circuit having a circuit breaker to protect. The illustration below shows the preferable breakdown of sub-circuits and panels, and is based on the successful implementation on a number of vessels. In the case below, only essential services are kept along with metering on the main panel. The lighting panel can be located anywhere practicable, as once circuits are on, lights are switched locally. Electronics panels are ideally a smaller panel located at the nav station (see nav station design chapter), the pump panel should be located in an accessible location, and in most cases the greatest concentration of pumps is midships to forward.

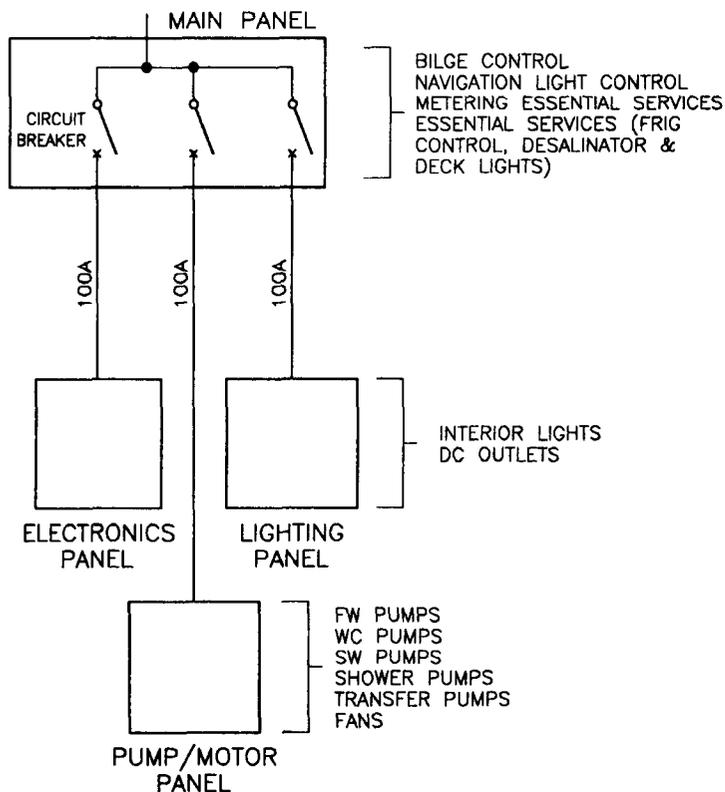


Figure 6-3. Distributed Power Systems.

6.4. DC Cable Installation. Cables are very often badly installed, and for the same effort with planning and correct procedures, a high quality job at the same cost can be undertaken. Observe the following criteria:

- a. Cable Types.** There are a number of important factors related to cable selection which are as follows:
- (1) **Tinned Conductors.** The use of tinned copper conductors is really essential, particularly where exposed to any saltwater spray or moisture. Plain copper will very quickly degrade and fail. The argument used against tinned copper is cost. The price differential is not that great and the reliability (and vessel resale increase) advantages far outweigh the lower priced plain copper conductor. After all you wouldn't use lower grade hull materials if you knew they would fail.
 - (2) **Insulation.** Double insulated cables should be used on all circuits to ensure insulation integrity. Additionally most insulation is temperature rated which has important implications with respect to ratings. In most cruising vessels PVC insulated and PVC sheathed cables rated at 75 degrees C are used. For classification societies Butyl Rubber, CSP, EPR or other insulating materials are specified which have higher temperature ratings and subsequently also have higher current capacities.
- b. Nominal Ratings.** All cables have nominal cross sectional areas and current carrying capacities. Nominal ratings are also given at specific temperatures, typically 20 degrees C. The principal cable sizes and ratings are given for twin conductors in Table 6-1. I always recommend standardisation of cable sizes, and this reduces the cable type and size to only two in most cases, which is both cheaper and easier.

Table 6-1. Typical DC Cable Nominal Ratings.

Conductor Size	PVC (Heat Resisting)	Butyl Rubber (Lloyds 100A1)	Resistance Ohms/1000m
1.0 mm ²	11.0 Amps	12 Amps	18.84
1.5 mm ²	14.0 Amps	16 Amps	12.57
1.8 mm ²	15.0 Amps		10.50
2.5 mm ² (14 AWG)	20.0 Amps	22 Amps	7.54
4.0 mm ² (12 AWG)	27.0 Amps	30 Amps	4.71
6.0 mm ² (10 AWG)	35.0 Amps	38 Amps	3.14
10.0 mm ² (8 AWG)	49.0 Amps	53 Amps	1.82
16.0 mm ² (6 AWG)	64.0 Amps	71 Amps	1.152
25.0 mm ² (4 AWG)	86.0 Amps	93 Amps	0.762
35.0 mm ² (2 AWG)	105.0 Amps	119 Amps	0.537
50.0 mm ² (1 AWG)	127.0 Amps	140 Amps	0.381
60.0 mm ² (0 AWG)	150.0 Amps	160 Amps	0.295
70.0 mm ²	161.0 Amps	183 Amps	0.252

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c. **Derating Factors.** All cable current carrying capacities are subject to derating factors:

(1) **Temperatures.** All cables have nominal ratings temperatures. In any installation where the conductors exceed that temperature the current carrying capacity of the cable is reduced. This is important in engine spaces.

(2) **Bunching.** Where cables are bunched in a large loom, derating occurs.

d. **Duty Cycles.** Heavy current carrying cables such as those used on windlasses, winches and starter motors are in fact only used for short durations. As there is a time factor in the heating of a cable, smaller cables can be used. The table shows battery cable ratings which are rated at 60% duty.

Table 6-2. Battery Cable Ratings.

Conductor Size	Current Rating 60% Duty Cycle
8 B & S (8 mm ²) (8 AWG)	90 Amps
6 B & S (15 mm ²) (6 AWG)	150 Amps
3 B & S (26 mm ²) (4 AWG)	200 Amps
2 B & S (32 mm ²) (2 AWG)	245 Amps
0 B & S (50 mm ²) (1 AWG)	320 Amps
00 B & S (66 mm ²) (00 AWG)	390 Amps

6.5. Voltage Drop Calculation. This subject is one of the most discussed and feared of all. Voltage drop must always be a consideration when installing electrical circuits. Unfortunately many of the voltage drop problems are created by the poor practice of trying to install cables and wiring to the minimum cable size possible. Voltage drops are more commonly caused by bad connections, not the cable. The maximum voltage drop in 12 volt systems is ideally 0.5 volts with a maximum of 0.7 volts. The voltage drop problem is prevalent in starting and charging systems, and in long runs to mast equipment, notably navigation lights which can cause reduced light outputs and therefore are illegal. There are many methods of calculating voltage drop with respect to choosing cable sizes, many are confusing and leave you a little light headed. To calculate voltage drop is the proper and simple application of Ohms Law. The formula is as follows:

$$\text{Voltage Drop (Volts)} = \text{Current (Amps)} \times \text{Resistance of Cable (Ohms)}$$

a. **Current.** The current value should be the rated current of the cable. Typically I standardise on 14-15 amp rated cable (1.5 - 1.85 mm²). In most cases the connected load will be significantly less than this. If you have a circuit which has equipment rated at 5 amps and permanently connected and where no other load can be applied then you can also calculate using that figure based on the above listed cable.

- b. **Resistance of Cable.** All cables have nominal resistance values, which are given as ohms per 100 or 1000 metres. In the DC circuit under calculation, the total cable run must be measured and doubled to account for the return circuit. In the typical maximum run length of 10 metres (excepting mast circuits) the resistance of the above cable is typically around 10.5 ohms per 1000m at 20 degrees. This gives a value of 0.105 ohms per 10 metres, so doubled the resistance is 0.21 ohms. As the calculation shows, this cable is not suitable for the loads of 10 amps and 5 amps is a marginal.

$$\text{Voltage Drop (2.1 volts)} = 10 \text{ Amps} \times 0.21 \text{ Ohms}$$

$$\text{Voltage Drop (1.05 volts)} = 5 \text{ Amps} \times 0.21 \text{ Ohms}$$

- c. **Line Losses.** This is another measure of power lost within a resistive line and is also called copper loss. It must be noted that the current is squared, so for every increase the losses are much higher. The calculations below are based on a typical 40-45 foot yacht electrical system and show both volt drop and line losses for each circuit at rated load on the two most common problem circuits. Where you design to the lower limit the losses can be quite large. In this case the formula is as follows:

$$\text{Line Loss (watts)} = \text{Current Squared (Amps)} \times \text{Resistance (Ohms)}$$

- d. **Anchor Windlass.** These must be calculated at working and peak loads. As the calculations show, a larger cable size will ensure less voltage drop and line losses.

Working load current 85 amps, cable run 12 metres, CSA = 35 mm², rating = 125 amps, resistance = 0.537 ohms per 1000m.

$$\text{Voltage Drop (1.1 volts)} = 85 \text{ Amps} \times 0.013 \text{ Ohms (2 x 0.006 ohms)}$$

$$\text{Line Loss (93 watts)} = 85^2 \times 0.013$$

Max load current 125 amps, cable run 12 metres, CSA = 35 mm², rating = 125 amps, resistance = 0.537 ohms per 1000m.

$$\text{Voltage Drop (1.6 volts)} = 125 \text{ Amps} \times 0.013 \text{ Ohms (2 x 0.006 ohms)}$$

$$\text{Line Loss (203 watts)} = 125^2 \times 0.013$$

- e. **Tricolour.** Load current 2 amps, cable run 40 metres, CSA = 2.5 mm², rating = 20 amps, resistance = 7.54 ohms per 1000m.

$$\text{Voltage Drop (1.2 volts)} = 2 \text{ Amp} \times 0.60 \text{ Ohms (2 x 0.30 ohms)}$$

$$\text{Line Loss (2.4 watts)} = 2^2 \times 0.60$$

6.6. Cable Installation. Fastening of cables in a vessel can take a number of forms. The emphasis must be on accessibility during installation, and for the later addition of circuits. Under no circumstances fibreglass in cables as some vessel manufacturers recklessly do. AC and DC cables can be run together in the same loom. The proviso is that both cables should be double insulated. Install cable as follows:

- a. **Conduit.** If it can be installed during the construction phase, install PVC electrical conduits to isolated areas so that cables can be easily pulled in, replaced or added to. These offer good mechanical protection to cables. In these cases single insulated tinned cables can be used if the conduit runs back to the switchboard. Do not install large bunches of cables in flexible conduits as they tend to move around and chafe. Do not use PVC conduits in machinery spaces.
- b. **Saddles.** Cables can be neatly bunched together and PVC or stainless saddles used to secure them. Saddles should be placed no more than 150 cm apart to prevent cable loom sagging and movement during service. I prefer the use of PVC conduit saddles, which come in a variety of sizes. Ideally I run a central cableway down one side of the vessel. This is normally a wooden panel approximately 4 inches (20mm) wide and extends forward and aft of the switchboard. The panel is run through the backs of cupboards and suitable transit holes are made where necessary. The panel is then covered with a ply cover to prevent damage in lockers. Cables are then separated into signal or instruments and DC supply, and plastic saddled. Where instrument cables must cross over power cables, this should be at right angles to avoid induced interference. In new vessels the wiring can then be left until the fitout is nearly completed. For circuits to the other side of vessel, one or two easily accessible areas are provided to install these cables.
- c. **Hot Glue.** A hot glue gun is a useful way of fastening small or single cables above head liners, or in corners behind trimming and carpet finishes. It is useful where there is no risk of cables coming loose but must not be used on heavy or exposed cable runs.
- d. **Tiewraps.** The PVC tiewrap is universal in applications, and should be used where looms must be kept together, or where any cable can be securely fastened to a suitable support. Do not use wraps to suspend cables from isolated points, as this invariably causes excessive stress and cable fatigue. For internal ties you only need the white ones, any external ties should be black UV resistant.
- e. **Spirowrap.** PVC spiral wrapping is another extremely useful method of consolidating cables into a neat loom. If a number of cables are laying loose, consolidate them into some spiral wrap, and then fasten the loom using tiewraps.
- f. **Cable Marking.** Always mark cable ends to aid in reconnection and fault finding. A simple slide on number system can be used, or some of the labelling systems for use with nylon cable ties. These simply require use of a marker pen. Just ensure that it is permanent. The practice of colour coded wiring has diminished, and with all cable being red for positive and black for negative, polarity identification is easy.

6.7. DC Circuit Protection. The purpose of circuit protection is to limit overload and fault currents to the rated capacity of the supply cable. Circuit protection is not normally rated to the connected loads, although this is commonly done on loads which are considerably less than the cable rating, such as VHF radios or instrument systems. The two most common circuit protective devices are the fuse and the circuit breaker. Recent developments have seen the introduction of electronic tripping and reset devices, especially in conjunction with touchpad electrical panels. Protection factors are as follows:

- a. Fuses.** Fuses are still widely used, and although cheaper they have many disadvantages. Most fuses are of the glass type. There are either simple fuse holders or a combination fuse switch from Hienemann. The following factors are the disadvantages of fuses, and in my opinion there are no real advantages excepting a much lower initial capital cost.
- (1) **Rating Variations.** The typical fuse is not very accurate and can rupture as much as 50% above or below nominal current rating.
 - (2) **Service Fatigue.** Fuse elements fatigue in service with the fuse element properties altering and subsequently the rated value will alter. Vibration also commonly causes breakage of the glass, and the worst disadvantage is that when you're really in trouble you can't find a spare fuse.
 - (3) **Voltage Drop.** There is added contact resistance in the fuse holder between each contact and the fuse ends which commonly cause voltage drops, intermittent supply and heating.
 - (4) **Fault Finding.** This problem is amplified when a circuit has a fault and you go through a box of fuses on a trial and error fault finding exercise. A circuit breaker allows simple resetting. From my own, and many other vessel owners experiences, there is no place for fuse systems on yachts unless of course you enjoy that adrenalin rush as your navigation lights go out or autopilot stops and you feverishly try and locate, and install, a failed fuse in the middle of the night, in a force 9, and you are on a lee shore, and, and, well you know about Murphy's Law, and they say he was an optimist!
- b. Circuit Breakers.** The circuit breaker is the most reliable and practical method of circuit protection. Physically they are manufactured in press button aircraft types, toggle type, or rocker switch. Ideally they are used for circuit isolation and protection, combining both functions, which saves switchboard space, costs and installation time as well as improving reliability. Single pole circuit breakers are normally fitted to most vessels, however classification societies only allow these in grounded pole installations. This is because a fault arising on the circuit will provide a good ground loop and the large current flow will ensure proper breaker interruption. Double pole breakers are recommended for all circuits, as they will totally isolate equipment and circuits. This is a requirement of many classification or survey authorities.

- c. Circuit Breaker Standards.** Only install circuit breakers that are approved by UL, CSA or Lloyd's. Approvals for small vessel breakers categorise them as supplementary protectors. On my switchboards I use either Heinemann or ETA breakers, although makes such as Carling are also good. All makes are manufactured to high standards and are suitable for the demands of marine systems.
- d. Circuit Breaker Selection.** Circuit breakers must be selected for the cable size that they protect. The rating must not exceed the maximum rated current of the conductor. The cable sizes in Table 6-3 give recommended ratings for single cables installed in well ventilated spaces. Bunching of cables and high ambient temperatures require derating factors. Ratings are given according to IEC Standard 157.

Table 6-3. Circuit Breaker Selection Table.

Conductor Size	Current Rating	CB Rating
1.5 mm ²	7.9 - 15.9 Amps	8 Amps
2.5 mm ²	15.9 - 22.0	16
4.0 mm ²	22.0 - 30.0	20
6.0 mm ²	30.0 - 39.0	30
10.0 mm ²	39.0 - 54.0	40
16.0 mm ²	54.0 - 72.0	60
25.0 mm ²	72.0 - 93.0	80
35.0 mm ²	93.0 - 117.0	100
50.0 mm ²	117.0 - 147.0	120

- e. Discrimination.** The principle of discrimination in a circuit is extremely important and regrettably is rarely considered or installed on cruising yacht electrical systems. A circuit normally should have two or more overcurrent protective devices, such as the main and auxiliary circuit breakers installed between the battery and the load. The devices must operate selectively so that the protective device closest to the fault operates first. If the device does not operate, the second device will operate protecting the circuit against overcurrent damage and possibly fire.
- (1) Use circuit breakers with different current ratings. This effectively means that at a point on the time delay curve the first breaker will trip, if it does not and the current value increases the next will. A point is reached called the limit of discrimination. At this point the curves intersect and both breakers will trip simultaneously.
 - (2) Use circuit breakers with different time delay curves. This simply entails using breakers with differing time delay curves to achieve the same result.
 - (3) Use circuit breakers with different time delay curves, current ratings and different breaker types. This enables using all of the above to ensure discrimination.

- f. **Tripping Characteristics.** Characteristics are normally given by the manufacturer of the breaker and is a curve of current against time. The greater the current value over the nominal tripping value the quicker the circuit breaker will trip.

6.8.
circuit
isolation
characteristics

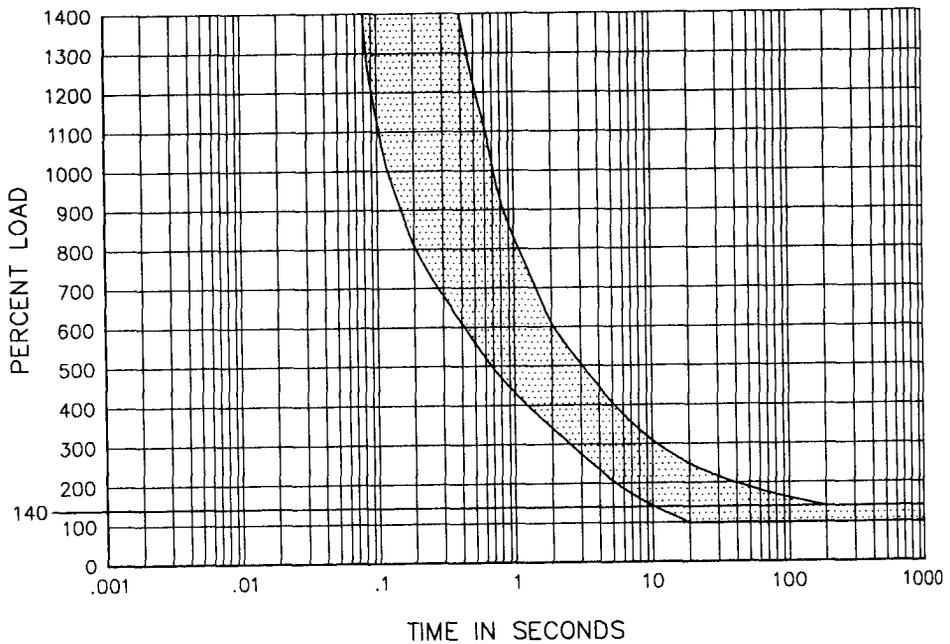


Figure 6-4. Circuit Breaker Time Delay Curve.

6.8. Supply Circuit Isolation. Individual circuits are isolated either by the circuit breaker or a switch. Main DC supply to the switchboards must also have isolation. In many installations this is performed by the ubiquitous battery changeover switch. Better alternatives are as follows:

- a. **Single Pole Switches.** If a system is designed and installed as I have recommended then this will be replaced by a single pole isolator rated at 100 amps.
- b. **Double Pole Switches.** In steel and alloy vessels the isolation should be a double pole switch and these are normally rated at around 300 amps. They are a good idea in all vessels as this eliminates the feed back into the system from lightning strikes. The double pole switches are also a requirement of many survey and classification societies.
- c. **Isolator Location.** Isolation switches should be installed as close as practicable to the battery bank. They should also be mounted as high as practicable above possible bilge and flooding levels.
- d. **Short Circuit Protection.** Survey authorities also require short circuit protection mounted adjacent to the battery, but they should not be able to cause an arc or ignition of gas from batteries. My normal practice is to install two 100 or 125 amp DC circuit breakers located as close as practicable to the batteries, one for the windlass and one for the panel supply.

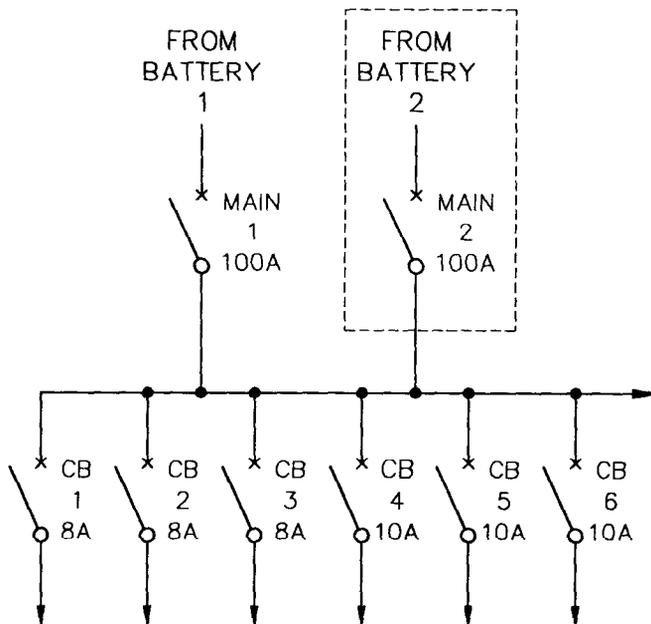


Figure 6-5. Supply Circuit Isolation.

6.9. DC Cable Connections. Cable connections are the single greatest cause of electrical problems on a vessel. The following practices should be used to ensure optimum reliability:

a. Cable Ends. Cable ends should simply have the insulation removed from the end, without nicking the cable strands. Prepare cable ends as follows:

- (1) The bare cable strands should be simply twisted, and inserted in the terminal block or connector of a similar size.
- (2) Ensure there are no loose strands, and this is very easy to do. If you are terminating into an oversize terminal block, twist and double over the cable end to ensure that the screw has something to bite on.
- (3) For cable insertion under a screw do not use crimp cable pin connectors, they simply add contact resistance into the circuit. The holding clamps on most terminals are designed for cables, not flat connectors.

b. Soldered Ends. Do not solder the cable ends. This practice is widespread and there is a widespread misconception that this will make good connections and prevent cable corrosion. I have yet to find any internal cable that failed due to corrosion except bilge pump connections and they were aggravated by direct salt water contact and electrical interaction. There is controversy on this issue, but from experience solder in fact causes many problems as follows:

- (1) The solder travels up the conductor causing stiffness. This causes greater vibrational effects at the terminal with resultant fatigue and failure. In most cases the soldering is poorly done with a high resistance joint being made.
- (2) A soldered cable end also prevents the connector screw from spreading the strands and making a good electrical contact, causing high resistance and heating. The proviso is that you should use connectors of the correct size for the cable.

6.10. Solderless Terminals. The most practical method of cable connection is the solderless terminal or crimp connector. These are colour coded according to the cable capacity that can be accommodated. Terminals such as the STAKON types are designed and manufactured according to NEMA standards, which cover wire pullout tension tests, and voltage drop tests. Quality terminals will meet UL and CSA standards. Two important points when using connectors:

- a. Crimping Tool.** Only use a quality ratchet type crimping tool, not a cheap pair of squeeze types, which do not adequately compress and "capture" the cable subsequently causing failure as the cable pulls out of the connector sleeve.
- b. Crimping.** A good joint requires two crimps. Always crimp both the joint and the plastic behind it. Ensure that no cable strands are hanging out. Poor crimping is one of the major causes of termination failure that I encounter.

Table 6-4. Cable Connector Standard Table.

Colour	Cable Size Range	Current Rating
Yellow	3.0 to 6.0 mm ²	30 Amps
Blue	1.5 to 2.5 mm ²	15 Amps
Red	0.5 to 1.5 mm ²	10 Amps

- c. **Spade, Tab, Lucar Connectors.** These are the most commonly used connectors. When using them observe the following:
- (1) **Connector Sizes.** Always use the correct spade connectors for the cable size.
 - (2) **Connector Security.** Spade connectors are easily dislodged. As there is a tendency for these types to slip off the back of circuit breakers ensure they are tight to push on. Ensure that the spade actually goes on the tab, and not in between insulation sleeve and the connector. With switchboards I like to apply a dab of solder, or even simply a drop of silicon to prevent the connector from working loose.
- d. **Ring Connectors.** Ring connectors are used on all equipment where screw, bolt and nut are used. They should also be used on any equipment subject to vibration, or where accidental dislodgement can be critical, particularly switchboards.
- (1) **Connector Hole.** Always ensure that the hole is a close fit to the bolt or screw used on the connection, to ensure good electrical contact and use spring washers.
 - (2) **Creepage.** One practical method used to prevent nut creepage is to dab on a spot of paint.
- e. **In-Line Cable (Butt) Splices.** Where cables require connection and a junction box is impracticable, use insulated in-line butt splices. This is more reliable than soldered connections, where a bad joint can cause high resistance and subsequent heating and voltage drop. use heat shrink insulation over the joint to ensure waterproof integrity is maintained. There are connectors that when heated form a watertight seal by the fusing and melting of the insulation sleeve. These can be ideal for bilge pump connections.
- f. **Pin Terminals.** Pin terminals can make a neat cable termination into connector blocks, however from experience I have found these to be unreliable simply because vibration and movement work them loose and in most cases they do not precisely match the connector block terminal and make an inadequate electrical contact.
- g. **Bullet Terminals.** These are useful where used in cabin lighting fittings. I often use these on all cable ends, female on the supply and male on the light fitting tails. This makes it easy to disconnect and remove fittings, especially where they are permanently installed in the headlining.

6.11. DC Junction Boxes. Junction boxes are the most practical way to terminate a number of cables, especially where access is required to disconnect circuits. There should be a minimum of junction boxes and the following are virtually standard in any installation:

- a. **Mast Circuits.** The mast circuits should all have a junction box in a dry location under the deck. This will include a box for lighting circuits, a box for masthead wind instrument, a VHF coaxial cable junction box or in-line connector, and a radar junction box. This will enable easy disconnection for mast removal, and faultfinding. The Index (Thrudex) models illustrated below are by far the best type available and give a neat and professional job.
- b. **Lighting Circuits.** To reduce cables radiating back to the switchboard and also minimise voltage drops, I use a junction box forard and aft to power up lighting circuits. The best for these where several cables are to be paralleled are the small domestic mini junction boxes that incorporate three terminals. They are quite suitable as long as a dry location is chosen, such as a cupboard or behind a panel.

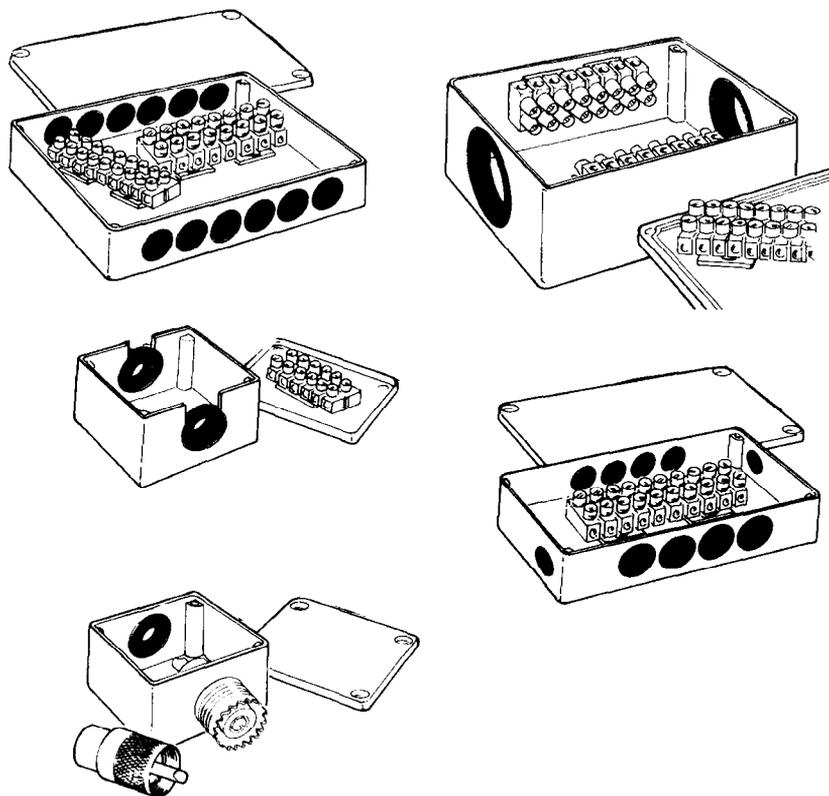


Figure 6-6. Index (Thrudex) Junction Boxes.

12. DC Switchboards. A well designed and manufactured switchboard is a prerequisite for good circuit control, operation, monitoring and protection.

a. Material. Metal or plastics? This is the big question. Survey requirements and most classification societies specify a non-conductive, non-hygroscopic material although most metal panels gain approval. I have outlined the various advantages of each type:

(1) **Plastics.** These multilayer boards are non-conductive and are made of traffolyte or bakelite. Circuit identification is done by engraver, which cannot be rubbed off. The boards are also corrosion resistant, and do not scratch easily. The panel illustration is of such a panel for a trimaran fitout that I recently completed.

(2) **Metal.** Metallic anodised aluminium panels are generally etched with appropriate circuit identification, and they are very attractive. They are however conductive, and faults and shorting can occur to the panel. Metallic panels must always be suitably grounded. After some use, the etching can wear away, and the circuit names obscured. The majority of off-the-shelf panels such as Marinetics, BME and Mastervolt are anodised aluminium.

b. Fireproofing. Survey authorities specify the internal part of the switchboard be lined with a fire resistant lining. Line all interior walls with an appropriate sheeting, and this will help in containing any fire that may arise in severe failure conditions.

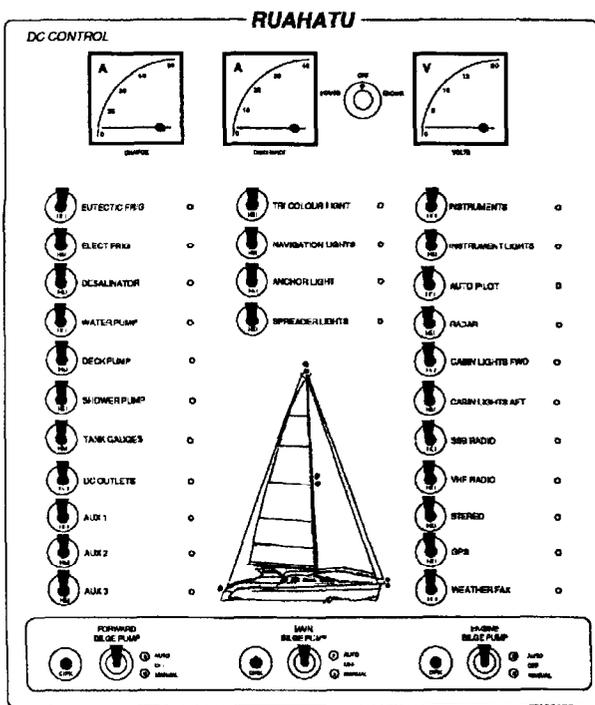


Figure 6-7. Switchboard Arrangement.

c. **Voltmeters.** A good quality voltmeter is essential for properly monitoring battery condition. As a battery has only a range of approximately one volt from full charge to discharge condition, accuracy is crucial.

- (1) **Analog Voltmeters.** These are the most common. The sense cable should go directly back to the battery, although on service battery connections most connect directly to the switchboard busbar. Direct connection gives greater accuracy and less influence from local loads. Voltmeters should be of the moving iron type and also have a fuse installed on the positive input cable. Switching between batteries to voltmeter is through a double pole, centre off toggle switch or a multiple battery rotary switch. Meters must be zeroed properly, and a check made against a digital multimeter to verify error. Half a volt error is quite common. It is prudent to switch off the meter after checking.
- (2) **LED Indicators.** These devices are often used as a voltmeter substitute. They are not recommended as they do not give the precise readings required. Some units have a high and low battery voltage alarm incorporated. An auxiliary output on alarms can also switch off power or charging system, which sounds fine but in practice can be a nuisance.
- (3) **Digital Voltmeters.** Digital voltmeters are making an appearance on vessels, and are far more accurate. They are susceptible to voltage spikes and damage, as well many have maximum supply voltage ranges of 15 volts. In this case they should have some form of over-voltage protection and power supply voltage regulation. There are a number of types, and these include Liquid Crystal Displays (LCD) and Light Emitting Diodes (LED). LED types consume power, and although vessel manufacturers install them because they look pretty, an LCD meter consumes much less and is more practical.

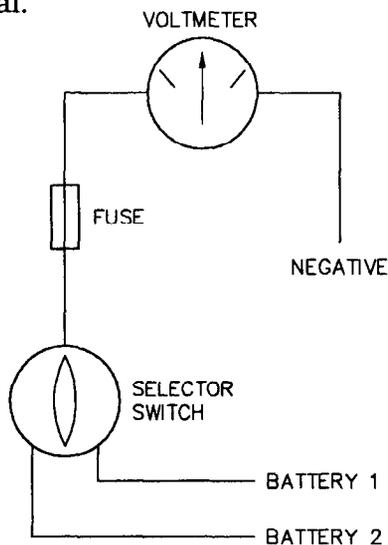


Figure 6-8. Voltmeter Connection.

d. **Ammeters.** Ammeters are essential on the switchboard input positive to monitor service battery discharge levels. Although useful, an ammeter on the charging system can indicate that current is flowing, however I rarely install them. (when you get the price on a quality 80 amp shunt ammeter you will probably omit it as well). You do not know what should be flowing into the battery, and peace of mind is the greatest benefit. A voltmeter will tell you if the battery is charging at the correct level. Similarly the options are similar to voltmeters in that both analog and digital are possible.

- (1) **Analog Ammeters.** Analog ammeters should be selected on the calculated operating range. A switchboard load meter can be scaled to read 0-40 amps, and a charging system ammeter scaled to read 90 amps. This will enable overcurrent tolerance which can happen without destroying or damaging it. Cheaper ammeters are of the in-line type. The cable under measurement passes through the meter. The major failing of these is that often considerable cable runs are required with resultant voltage drops. Additionally if the meter malfunctions damage can occur. Always use a shunt ammeter.
- (2) **Ammeter Shunt.** A shunt simply allows the main current to flow while monitoring and displaying a millivolt value in proportion to the current flowing. The advantage is that only two low current cables are required to connect the ammeter to the shunt, and the risk of damage is reduced. Do not run the main charging cables to where the meter is and connect it, that defeats the purpose, install a shunt in the line where ever practical and run sense wires back to the panel mounted meter.
- (3) **Digital Ammeters.** Digital ammeters are relatively new. The digital ammeter often uses a different sensing system. Instead of a shunt the digital ammeter has what is called a Hall Effect sensor on the cable under measurement. The Hall Effect transducer generates a voltage proportional to the intensity of the magnetic field it is exposed to. For vessel applications a 0-10 volt transducer output corresponds to a 0-200 amp current flow. Sensitivity is increased, and range reduced by increasing the number of coils through the transducer core.

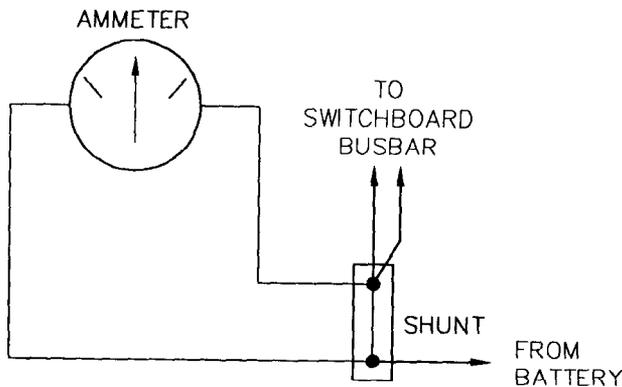


Figure 6-9. Ammeter Connection.

- e. **Digital Circuit Monitors.** A number of new systems have emerged. They are relatively sophisticated in that some units monitor power out, either in amps or amhours, and power into the batteries. Other units are simply a single monitor panel, capable of monitoring up to 4 separate circuits, either voltage or current. These also incorporate an automatic low voltage alarm function on all channels with visual and audible indication.
- (1) **Bank Manager II.** These units from Ample Power have a number of monitoring functions that includes voltage and current, high and low voltage alarms, amp-hours used and amp-hours remaining, charging current and battery temperatures for the principal battery with voltage monitoring and alarms on battery 2.
 - (2) **VDO BATTMAN II.** This VDO unit is a very comprehensive unit for battery bank monitoring. It has multifunction display indicating battery capacity in amp-hours, actual capacity consumed, total amhours put back in though charging. Additionally it has an accurate digital voltmeter.
- f. **Battery Level Alarms.** These relatively simple monitoring devices are connected to the main switchboard busbars. They are set to activate on both high and low voltage levels with both an audible and visual indication. The voltage activation levels are typically 11.8 volts for a low alarm, and 15.5 volts for a high voltage. If you have no alarm mute switch, it will annoy you to the extent that you have to charge the batteries, which is not a bad thing.
- g. **Protection Devices.** Circuit protection devices are normally either fuse or circuit breaker. The following should be observed.
- (1) The circuit breakers should be laid out on the board in logical, functional blocks. Mastervolt have functional standard size panels that interlock to achieve the same result.
 - (2) The ideal is to group the navigation lights together, the electronics in another block, and the pumps and auxiliaries in another. This makes selection in total darkness a lot easier. In some cases it is often practical to use press button breakers on one group, and lever types on another to facilitate selection or offer easy recognition. This can be improved further by ensuring that one busbar feeds all high current intermittent loads, and other sensitive equipment on a second busbar.
- h. **Circuit Indicators.** Circuit breaker status indicators consist normally of two light types:
- (1) **LED.** Circuit status is generally a simple red LED. Green is rarely used, although logically this is the right colour. Green LED's are less bright and more difficult to see in daylight conditions. An LED requires a resistor in series and this is typically valued at 560 ohms for 12 volts systems.

(2) **Filament Lamp.** Red filament lamps are also commonly used. The one disadvantage of these is that they consume power, typically around 40 mA. If there are twenty circuits on this adds up to a reasonable load on the system, and a needless current drain. If you have a very large switchboard, allow for the current drain. In many cases people assume they have a current leakage problem when in fact it is the switchboard indicators causing the drain.

i. **Busbars.** Fuses or circuit breakers should have a common supply busbar at the rear. My own practice is to put a separate busbar for each row of breakers and run a separate feed to each from the main positive link or from the discharge ammeter shunt. Circuit cables to the back of breakers should consist of one or more flexible looms with sufficient length to safely place the entire panel out from the mounting frame to facilitate access and work on it.

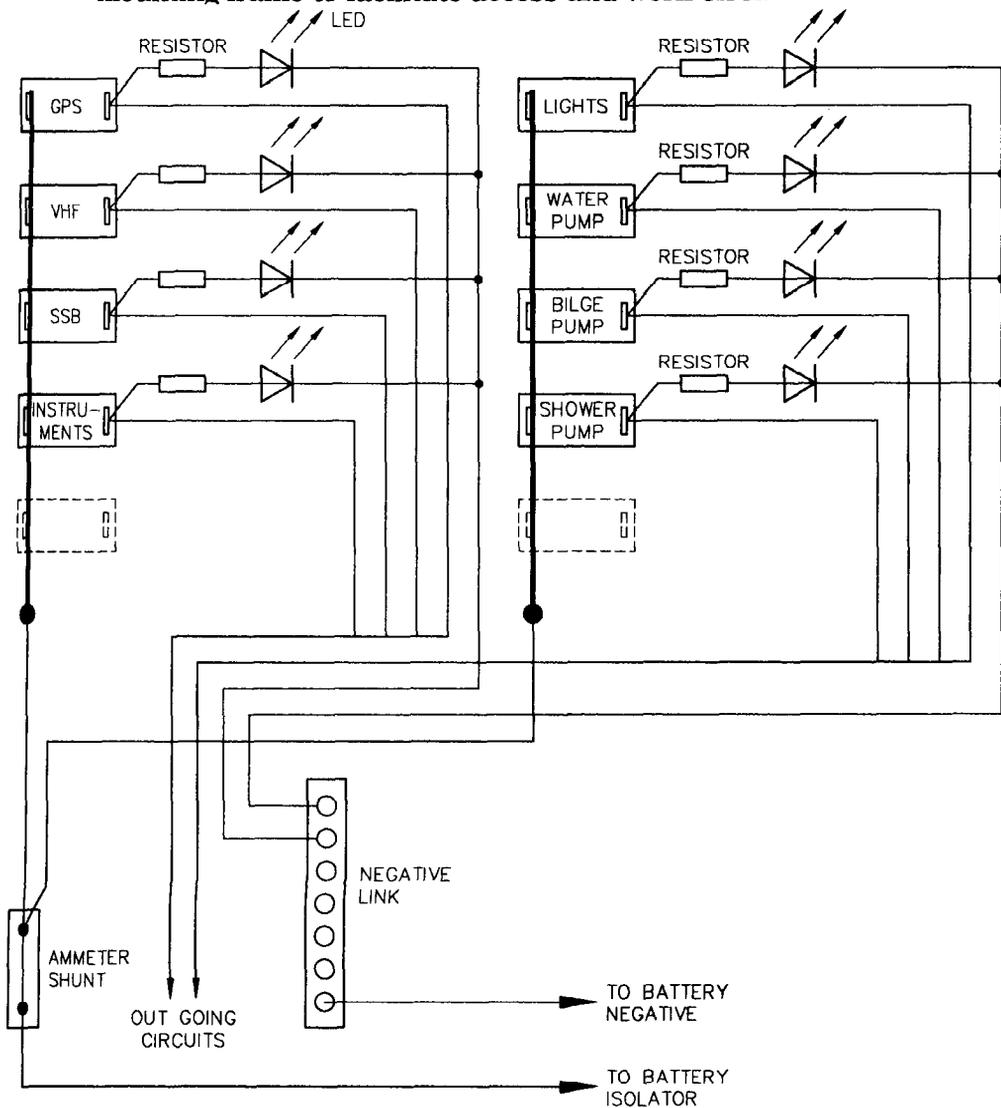


Figure 6-10. Switchboard Rear Connection Layout.

6.13. Switchboard Fault Diagnosis. There are a number of faults that routinely occur on switchboards, and their protective devices. The following faults and probable causes should be checked first. It is assumed that batteries are fully charged and that power is at the switchboard:

- a. **Circuit Breaker Trips Immediately at Switch On.** This is characterised by the ammeter showing in most cases an off the meter full scale deflection that shows the high fault current.
 - (1) **Load Short Circuit.** Check out the appropriate connected load and disconnect the faulty item before resetting.
 - (2) **Connection Short Circuit.** If after disconnection of the load the fault still exists, check out any cable connections for short circuit, or in some cases cable insulation damage.

- b. **Circuit Breaker Trips Several Seconds After Switch On.** This is characterised by the ammeter showing a gradual increase in current to a high value before tripping off.
 - (1) **Motor Seizure.** This fault may arise if the electric motor has seized.
 - (2) **Load Stalling.** This fault is usually due to a seized pump.
 - (3) **Insulation Leakage.** This fault is usually due to a gradual breakdown in insulation, such as in a wet bilge area pump connection.

- c. **There is No Power After Circuit Breaker Switch On.** If after checking that power is absent at the equipment connection terminals, check the following:
 - (1) **Circuit Connection.** Check that the circuit connection has not come off the back of the circuit breaker. Also check the cable connection to the crimp connection terminal.
 - (2) **Circuit Breaker Connection.** On many switchboards, the busbar is soldered to one side of all distribution circuit breakers. Check that the solder joint has not come away. In some cases breakers have a busbar that is held under breaker screw terminals, check that the screws and connection are tight.
 - (3) **Circuit Breaker.** Operate the breaker several times. In some cases the mechanism does not make proper electrical contact and several operations usually solve the problem by wiping the contacts.
 - (4) **Circuit Negative.** If all tests verify that the positive supply is present, check that the circuit negative wire is secure in the negative link.

- d. **Circuit Power On But No Indication Light.** The LED may have failed, and in some cases the resistor. Also check the soldered connection to the circuit breaker terminal.

8.14. Membrane Touchpad Electrical Panels. A number of yacht manufacturers have introduced these switchboards. I have heard mixed reports on systems reliability, and there are some on the market which I do not recommend and some systems I have successfully installed.

- a. **Relay System.** These have a relay for circuit control, where activation of the pad switches a circuit relay. The relay is normally a 30 amp rated single pole device which acts as an isolator.
 - (1) **Automatic Protection.** Normal fuses and circuit breakers are not used. Current sensing is carried out by using Hall Effect devices, which detect the magnetic field and supplies an output to a variable tripping point controller.
 - (2) **Standard Protection.** Circuit breakers are used. These are normally mounted on the switching control box. When a fault or overload is detected the circuit breaker trips and requires manual resetting.
- b. **Solid State System.** These systems use the touchpad to activate a solid state device, which is used as the switch. This can be a power transistor or an SCR. Buyers should be very wary, as many have an atrocious reliability record, so ask for a few references first before investing in these panel types. The main problem is that electrical system spikes often damage switching components, and the entire panel fails.

8.15. Mast Cabling. Mast cabling is a common failure area, and many of the problems can be avoided if cables are installed properly. Observe the following:

- a. **Junction Boxes.** The most common failure area is the junction box. If internal to the vessel a good water resistant box should be installed. If external, and this should be a last resort, a waterproof box is required. Always leave a loop when inserting cable into the box. If water does travel down the loom, this will drip off the bottom of the loom and will not enter and corrode the junction box terminals or connections.
- b. **Cabling.** The second problem area is cabling. The following factors should be noted:
 - (1) **Cable Types.** The major problem is the use of single insulated untinned cables, generally of an under-rated conductor size. The single insulated cables easily chafe through and short, unless enclosed in a conduit. Small conductor size causes many volt drop problems with unacceptable low light outputs as a result.
 - (2) **Negative Conductors.** These days, the tricolour is normally a dual anchor light fitting. These use a 3 wire common negative arrangement. The same arrangement is used for combination mast-head and foredeck spotlights. Under no circumstances use the mast as a negative return as I have found on some vessels, install a negative wire to each light fitting.

(3) **Cable Support.** Cabling must also be properly secured w/ the mast. Weight of a cable hanging down inside a r causes fatigue and more importantly commonly ca fouling of internal halyards. If unenclosed, the halyards whip against cables, often severing conductors in multi instrument cables or severely damaging insulation. Ca should be fastened along the entire length, or be enclose conduits.

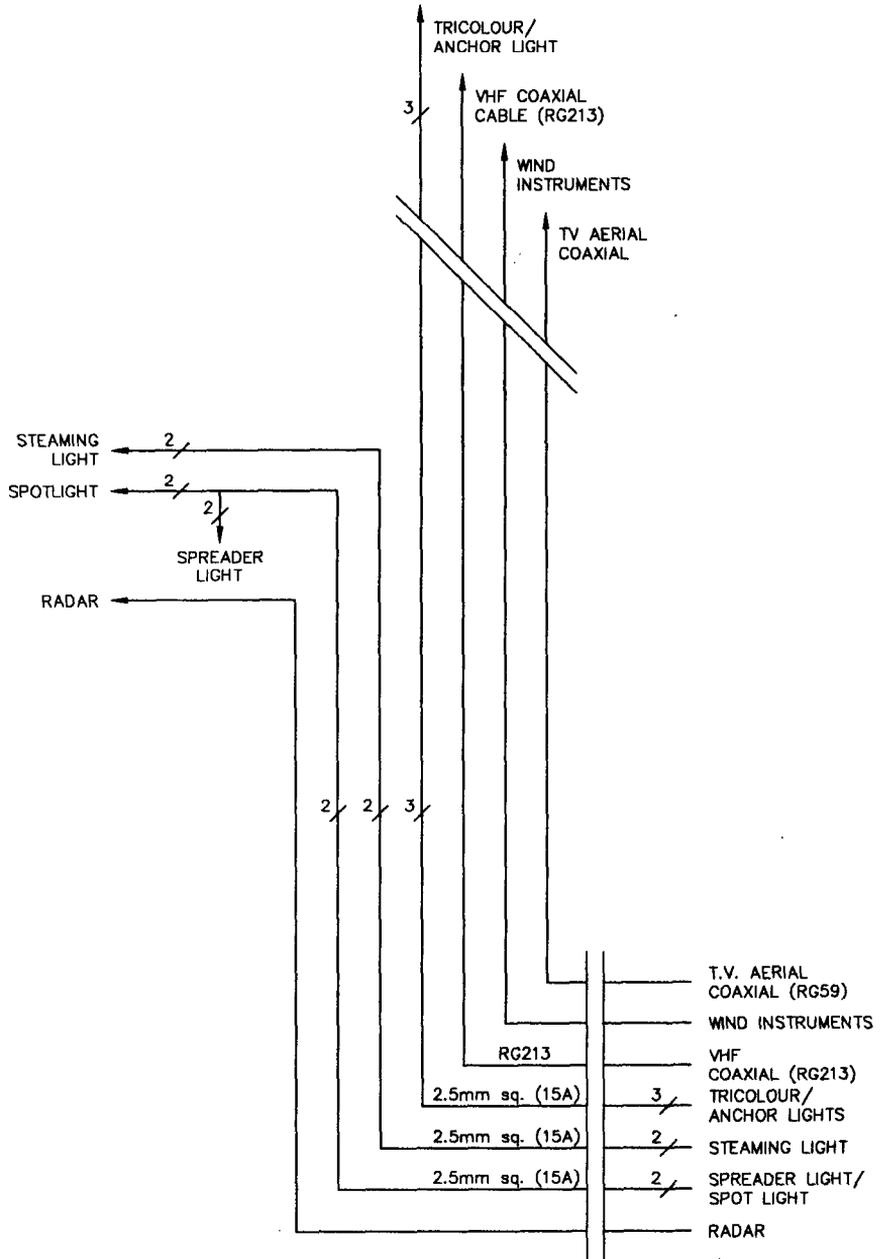


Figure 6-13. Mast Cabling Diagram.

16. Mast Cabling Fault Finding. Mast fault finding is probably one of the most common problem areas. The mast subjects cables to all of the worst damaging factors, such as vibration, exposure to salt water, stretching and mechanical damage. The following describes and illustrates fault finding procedures on mast wiring.

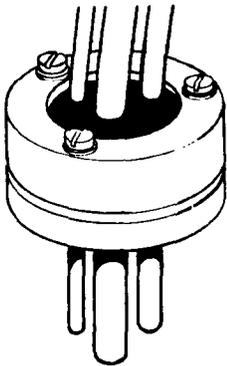
- a. **Tricolour/Anchor Lights.** If a light does not illuminate, invariably it will be due to a lamp failure. If the lamp is replaced and is still faulty check the following:
 - (1) **Check Supply.** Open the mast connection box and locate the appropriate terminals. Using a multimeter on the DC volts range, check that voltage is present at the terminals with power on. Many failures are due to poor contacts within terminal blocks, or corrosion of terminal and cable.
 - (2) **Continuity Test.** Turn the power off, and with a multimeter set on the resistance x1 range check between positive and negative terminals. The reading should be approximately 2-5 ohms with known good lamp installed. If the reading is over-range the light fitting or connection has failed or the cable has been damaged. Many tricolour-anchor lights have a plug and socket arrangement, and these sometimes give trouble.

- b. **Spreader Lights.** The above tests are also valid for spreader lights. On many vessels, spreader lights are a sealed beam unit in a stainless steel housing. It is very common to have shorts to the mast, as cables chafe through on the sharp edges. This problem is notorious for circuit leakages and increased corrosion rates on steel vessels.
 - (1) **Mast Short Circuits.** With a multimeter set on the resistance ohms x1k range check between mast and both positive and negative wires. The reading should be over-range. If you have any reading you have either a short or a leakage.
 - (2) **Check Supply.** Open the mast connection box and locate the appropriate terminals. Using a multimeter on the DC volts range, check that voltage is present at the terminals with power on.

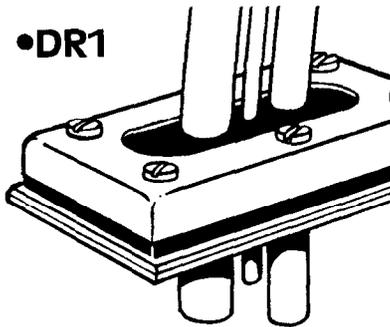
- c. **Cables Maintenance.** In any installation where cables are not enclosed in a conduit, and there are many about, the usual failure cause will be open circuit after an internal halyard has partially severed cable.
 - (1) **Mast Base Cable Exits.** Regularly examine cables where they exit the mast for signs of chafe. The loom unless covered in UV resistant sleeve will also suffer from rapid breakdown of insulation materials.
 - (2) **Mast Head Cables.** Regularly examine mast head cable exits for chafe. They chafe quickly if not secure as the weight hanging down often imposes considerable stresses. Ensure that co-axials, wind instrument and power cables have a reasonable loom to allow for shortening and repair. Tywrap cable loom securely to anchor it against down mast strains.

6.17. Deck Transits. Glands are designed to prevent cable damage and ensure a waterproof transit through a bulkhead or deck. A significant number of problems are experienced with the ingress of water through deck fittings and I have seen some amazing systems utilising pipes, hose etc. If typical figure 8 type cable is used, or small single insulated cables installed, it is virtually impossible to adequately seal them in cable glands. To overcome this problem, use circular multicore cables only or use the consolidation procedure to make a cable loom that can be put through a deck gland. There are basically two types of fittings used and the purpose designed Index (Thrudex) types are illustrated below in typical installations, and are by far the best on the market. Glands have to consider the structural material of a deck before selection. A steel deck requires a different gland type to a foam sandwich boat. The Index type of glands are either aluminium or plastic and caution should be used when installing aluminium glands on steel boats. The glands do have a neoprene gasket and stainless steel fastenings but I would recommend use of the plastic glands.

•D22 •D30 •D42



•DR1



•R22/5/8/10 •R25

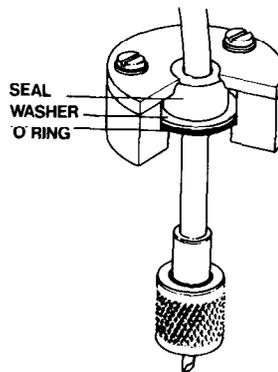
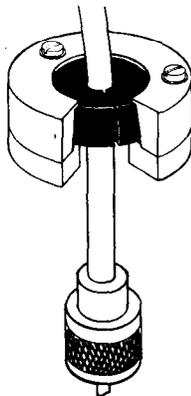


Figure 6-14. Deck Cable Glands.

- a. **Mast Cable Consolidation.** In most cases the mast is wired with single insulated cables. To properly put these cables through deck cable glands it is necessary to consolidate them into a single loom for use with a deck gland. One method is as follows:
- (1) Neatly make a cable loom and hold them in place with tiewraps. Keep the loom as circular as possible.
 - (2) Apply silicon compound to the loom, and ensure that it is worked through all cables. This will ensure that a solid core is made, and if done properly this will prevent water travelling down the cable loom.
 - (3) Apply a layer of black UV resistant spirowrap to the loom. Again, the spaces between the wrap should have silicon compound applied to fill any voids. The spirowrap effectively gives the cable loom a circular shape.
 - (4) Slide on a length of heatshrink tubing and shrink it in place. This gives an outer sheath.
 - (5) Use a suitable deck gland and pass the cable through the deck and connect into a suitable junction box.
- b. **Deck Plugs.** Deck plugs are required for a number of reasons. Instead of deck glands and junction boxes at a mast base, deck plugs are sometimes used which is a practical alternative. Also outlets for hand spotlights, or other equipment is commonly required. Many in use are of inferior quality and prematurely fail, generally when you need them most. Don't use the cheap and nasty chrome plugs and sockets, they aren't waterproof. The best units on the market are either the Bulgin type units from Index or those from Dri-plug. When using deck plugs observe the following:
- (1) **Deck Seal.** Ensure that the seal between deck and connector body is watertight. Leakage is very common on wet decks up forard where they are usually located.
 - (2) **Plug Cable Entrance.** Ensure that the cable seal into the plug is watertight. It is of little use having a good seal around the deck, and plug to socket if the water seeps in through the cable entry and shorts out internally as is often the case.
 - (3) **Connector Seals.** Most connectors have o-rings to ensure a watertight seal. Check that the rings are in good connection, are not deformed or compressed, and seat properly in the recess. A very light smear of silicon grease assists in the sealing process.
 - (4) **Connection Pins.** Ensure that the pins are dry before plugging in, and that pins are not bent or show signs of corrosion or pitting. Do not fill around the pins with silicon grease, as this often makes for a poor contact. Keep plugs and sockets clean and dry.

LIGHTNING PROTECTION

7.0. Lightning Protection. Virtually all classification societies, national marine authorities, ABYC etc lay down recommendations, but very few bother to adhere to the them. Of more importance is the startling statistic that over 10% of fatalities on cruising yachts are the result of lightning strikes.

7.1. Lightning Physics. Within the cloud formation, strong updrafts and downdrafts generate high electrical charges. When the voltage reaches a sufficiently high level both cloud to cloud and ground discharges occur.

- a. **Negative Cloud to Ground.** These strikes occur when the ground is at positive polarity and the cloud negative region attempts to equalise with ground.
- b. **Positive Cloud to Ground.** The positively charged cloud top equalises with the negative ground.
- c. **Positive Ground to Cloud.** The positive charged ground equalises with the negative charge cloud.
- d. **Negative Ground to Cloud.** The negatively charged ground equalises with the positive charged cloud top.

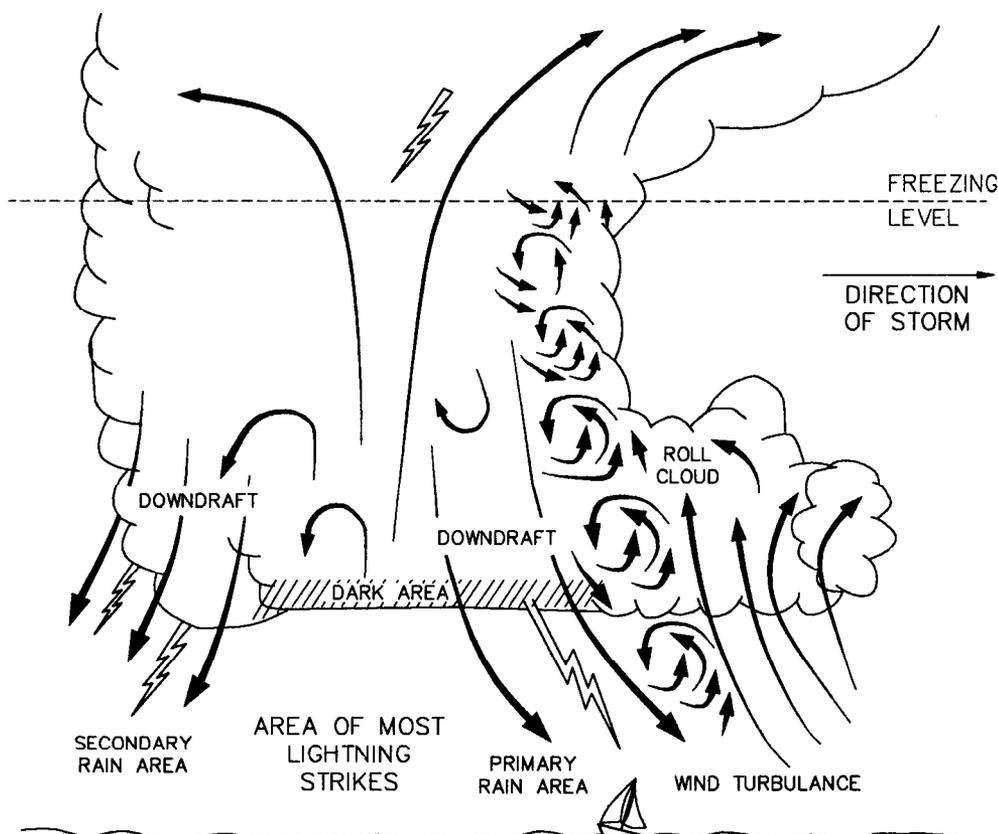


Figure 7-1. Cumulo-Nimbus Storm System.

2. **Lightning Components.** Lightning consists of a number of components which form a multidirectional flow of charges exceeding 200,000 amperes at over 30,000°C for a matter of milliseconds. The positively charged ions rise to the cloud top, and the negative ions migrate to the cloud base. Regions of positive charged ions also form at the cloud base. Eventually the cloud charge levels have sufficient potential difference between ground or another cloud to discharge. The processes are described as follows:

- a. **Leader.** The leader consists of a negative stream of electrons consisting of many small forks or fingers that follow and break down the air paths offering the least resistance. The charge follows the fork finding the easiest path as each successive layer is broken down and charged to the same polarity as the cloud charge.
- b. **Upward Positive Leader.** This is a positive charge that rises some 50 metres above the ground.
- c. **Channel.** When the two meet a channel is formed.
- d. **Return Stroke.** This path is generally much brighter and more powerful than the leader, and travels upwards to the cloud partially equalising the potential difference between ground and cloud.
- e. **Dart Leader.** In a matter of milliseconds after the return stroke, another downwards charge takes place following the same path as the stepped leader and return stroke, sometimes followed by multiple return strokes. The movements happen so fast that it appears to be a single event. This sequence can continue until the differential between cloud and ground has been equalised.

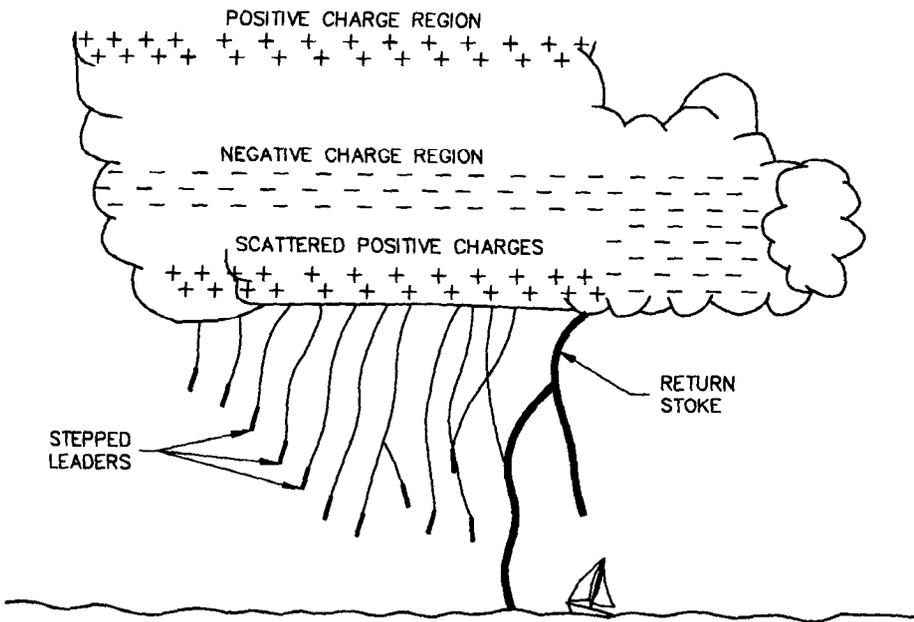


Figure 7-2. Lightning Process.

7.3. Lightning Protection Zone. The most reliable protection system is one that grounds any strike directly and the principles are as follows:

- a. Grounding.** The primary purpose of a grounding system is to divert the lightning strike discharge directly to ground through a low resistance circuit suitably rated to carry the momentary current values. This has the effect of reducing the strike period to a minimum, and reducing or eliminating the problem of side strikes as the charge attempts to go to ground. As electricity follows the path of least resistance to ground, little goes down the stays.
- b. Cone of Protection.** The tip of the mast, or more correctly a turned spike clear of all masthead equipment, gives a cone of protection below it. The cone base is the same as the mast height. This protective cone prevents strikes to adjacent areas and metalwork which in a yacht can mean stays, rails or other items lower than the mast head. Figure 7-3 illustrates the protective cone.

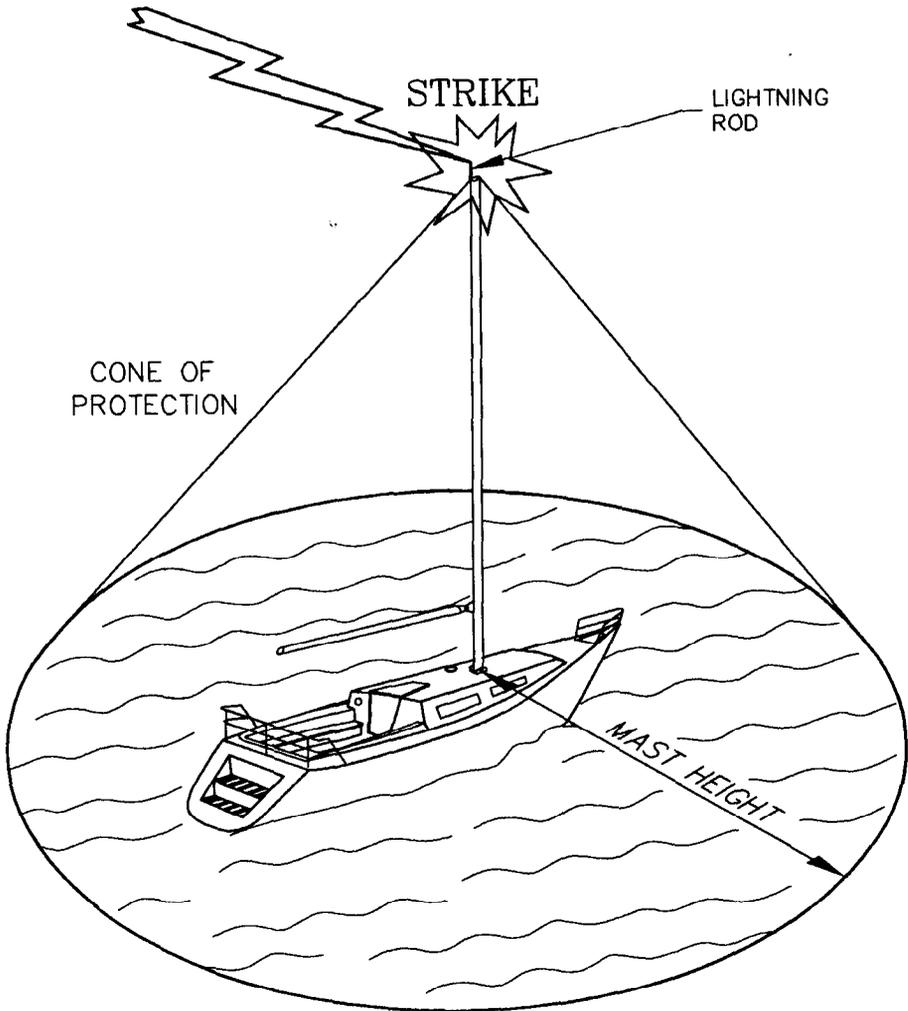


Figure 7-3. Cone of Protection.

- c. **Electromagnetic Pulse.** A vessel can have damaged equipment from a strike within a few hundred metres. Insurance companies don't like to accept claims on damage unless you can show total damage to mast-head systems. A strike sends out a very large electromagnetic pulse, which is a strong magnetic field. This field is induced into wiring and systems as a high voltage spike, doing just as much damage. If you suspect damage from an induced electromagnetic pulse from a localised lightning strike, check with all vessels adjacent to yours, and get statements to support the contention. Generally all the electronics will be out if this is the case as the mast and any wiring acts as a large aerial.
- d. **Sidestrikes.** It is common in very closely moored vessels and crowded marinas to have lightning strikes literally jump from vessel to vessel as it attempts to find ground on ungrounded vessels. Usually the strike exits from stays, chainplates and spreaders. In many cases the strike will go to water from the chainplates causing serious damage to hull and fittings.
- e. **St.Elmo's Fire (Brush Discharge).** This phenomena is more common on steel vessels and when it occurs usually precedes a strike, although the effect does not occur all the time. The vessel in effect becomes a large ground mass. The discharge is characterised by ionised clouds and balls of white or green flashing light that polarises at vessel extremities. The discharge of negative ions reduces the potential intensity of a strike. Damage to electrical systems is usually induced into mast wiring, as the steel hull itself acts as a large Faraday cage. For amusement, tell the insurance company that it was caused by St.Elmo's Fire!

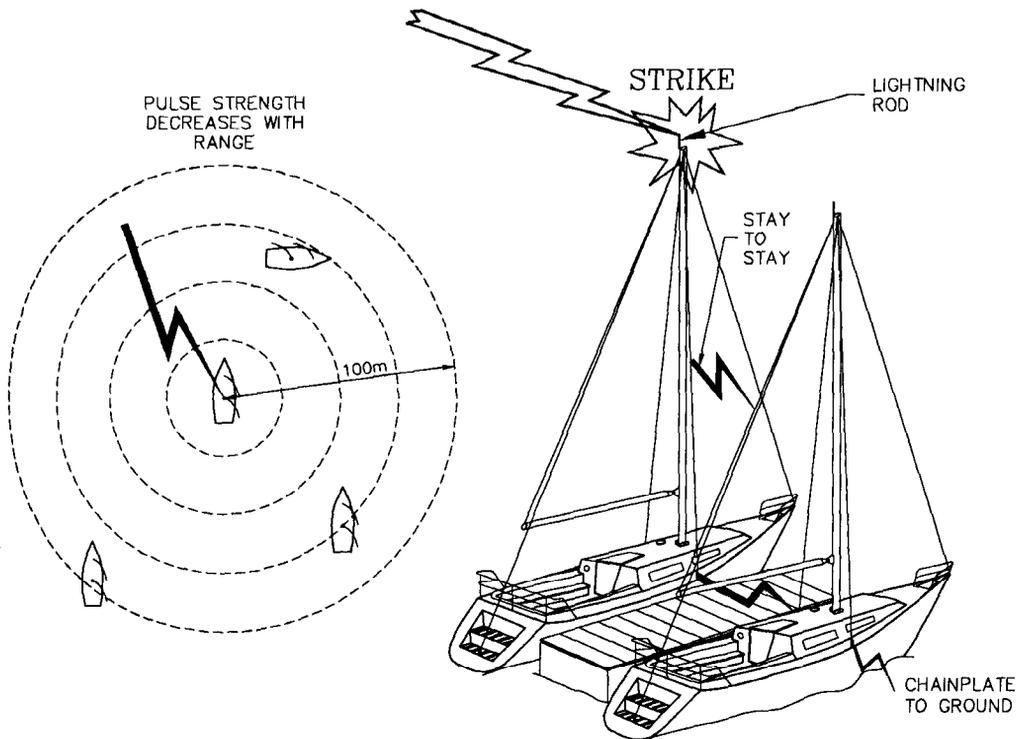


Figure 7-4. Electromagnetic Pulse Effect and Sidestrike.

7.4. Lightning Protection Systems. Most classification societies, American Boat and Yacht Council and other advisory bodies generally recommend lightning protection in the form of a directly grounded mast and spike. Other devices have come onto the market, and effectiveness is yet to be conclusively confirmed. Protection methods are as follows:

a. **Mast.** Lightning will generally strike the highest point, and take the path offering the lowest resistance to ground. The mast is usually the strike point. Note that a stainless steel VHF whip does not constitute any protection. Masthead systems are as follows:

- (1) **Mast Spike.** The mast spike ideally should be a copper rod with pointed end. To avoid metal interaction, stainless rods are commonly used but should be of a thicker section than the more conductive and lower resistance copper. The spike should be at least six inches higher than any other mast-head equipment, including VHF aerials. Many commercial units (Dynarod and Seaground) have an offset in the rod, which although not being the required straight section would be satisfactory. The purpose of the point being sharp is that it facilitates what is called point discharge. Ions dissipate from the ground and effectively cause a reduction in potential between the cloud and the sea. In many cases the strike may be of lower intensity or not occur at all.
- (2) **Lightning Protection Device (LPD).** This is an Italian development and consists of a high performance varistor. The device is designed to interact with the electrical charges of the initial stepped leader where current values are relatively low and avoid the return strokes. Charges accumulate on the atmospheric electrode and varistor poles. The varistor conducts and the charge condition on the electrode alters. These charges leave when some streamers form to meet the leader.

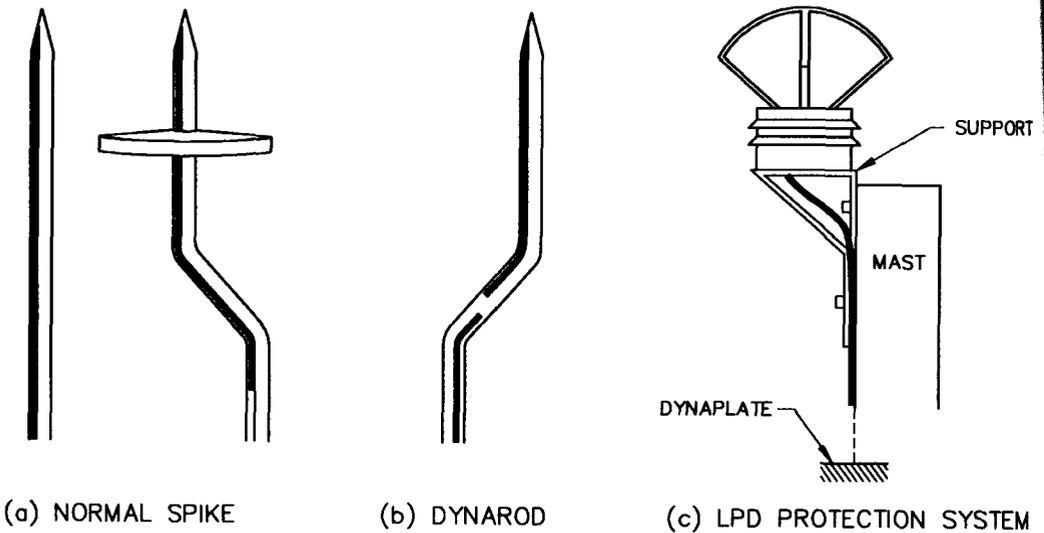


Figure 7-5. Mast-head Protection Systems.

b. **Mast Cable.** Much of the damage in a strike results from heat, as the large current flow into a resistive cable acts as a heater. The chapters on voltage drop are relevant here. The following factors must be observed:

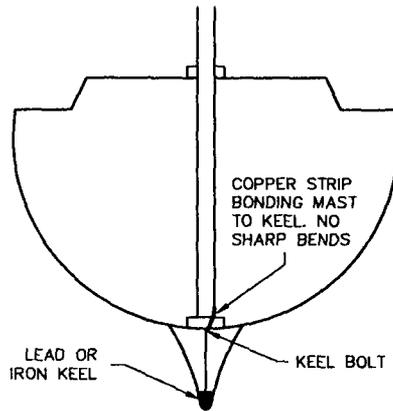
- (1) **Cable Sizes.** It is essential that cable cross sectional area is sufficient, typically 35mm² or greater.
- (2) **Cable Connectors.** Under no circumstances use soldered joints alone, as they will melt during a strike causing further havoc. Always crimp connections and ensure that all bonded connections are clean and tight. All connections must be bolted.

c. **Grounding.** A good ground requires direct and permanent immersion in sea-water. It must also have sufficient area to adequately dissipate the strike energy. Through hull fittings must never be used as a primary ground point unless you want to sink the vessel. The bonding cable from the mast base to the ground plate should be as straight as practicable without sharp corners as side discharges occur and this is called corona discharge. Similar side discharges can occur from boat to boat in crowded marinas. Normally I enclose the cable in high quality electrical conduit to reduce the possibility of side strikes on the cable, as electrical insulation will frequently break down under high voltage conditions. Connections should be as follows:

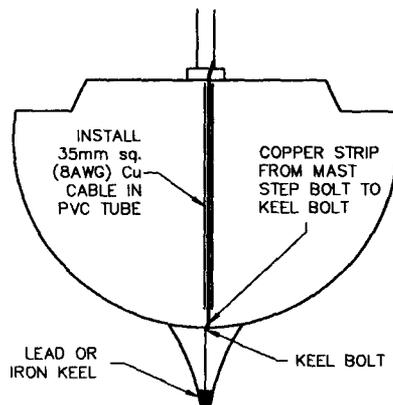
- (1) **Steel/Alloy Vessels.** Connection of the mast base with a large, low resistance bonding strap to the hull or as more practical the mast step is sufficient.
- (2) **GRP Vessels.** A keel acts as a good ground and is sufficient. Bridge out with a stainless link at least two keel bolts to spread the contact area. On multihulls you have to install a large separate ground plate, such as a radio ground (Dynaplate, Wonderbar or Seaground). This will ensure that there is a large and efficient ground area. Do not use the radio RF ground plate as the lightning ground. Never bond the lightning system to the corrosion system bonding, machinery or electrical system negatives or grounds. Never bond the lightning system to bronze through hull fittings.
- (3) **Wooden Vessels.** Wooden vessels normally have a metal mast track. The track should be properly grounded. If possible a copper strap can also be run, although this is not always practical. The same grounding method as GRP should be used by direct bonding to a ground plate or the keel. Some owners have installed gold plated ground plates, and by looking at nobility table it can be seen that a potential corrosive situation may occur.
- (4) **Emergency Ground.** A heavy gauge copper cable can be clamped to a stay over a half metre section. The other end should be clamped to a ground plate, and hung over the side. Do not use chains and anchors as they are ineffective as a ground.

d. **Corrosion Factors.** Considerable care must be taken when bonding various items of equipment into a lightning protection bonding system.

- (1) On steel and alloy vessels the hulls are the one ground plane for all equipment and all grounds are held at the same potential.
- (2) In GRP and timber vessels it can be more complicated, but problems may arise where indiscriminate bonding of through hull fittings and other items is carried out. It is easy to create differences of potential between various items creating a corrosion nightmare.
- (3) After connecting up a lightning system, it is prudent to monitor the corrosion rate of anodes, and observe any underwater bonded items.



KEEL STEPPED MAST
EXTERNAL KEEL



DECK STEPPED MAST
EXTERNAL KEEL

Figure 7-6. Bonding and Grounding Arrangement.

e. **Bonding.** Most authorities recommend that all stanchions, chainplates, and large metallic equipment such as stainless water tanks should be bonded to the lightning ground. Failure to bond can result in side flashes as these can offer an alternative path. The bonding should be made at the point closest to the main conductor. Bonding recommendations are as follows:

- (1) **Stay Grounding.** I prefer not to bond the stays and chainplates as often recommended. My reasoning behind this is that if a good low resistance path is made from mast to keel or groundplate the strike energy will be directed that way. Grounding stays offers alternative high resistance paths, encouraging side strike activity. Current flows can also cause crystallisation and permanent damage to stainless stays and fittings in a severe strike (try and get that past an insurance company!).
- (2) **Corrosion.** Bonding must be undertaken with care. Dissimilar metals such as the aluminium mast, copper strap, and steel must be interconnected to ensure no galvanic corrosion can occur. More importantly interconnection of various grounding systems must be undertaken with great care. Observe notes in the corrosion chapter.
- (3) **Internal Bonding.** It is only necessary to bond internal metallic equipment within six feet of the mast. In practice this is rarely water tanks under bunks etc, but should include tankage under the cabin sole.

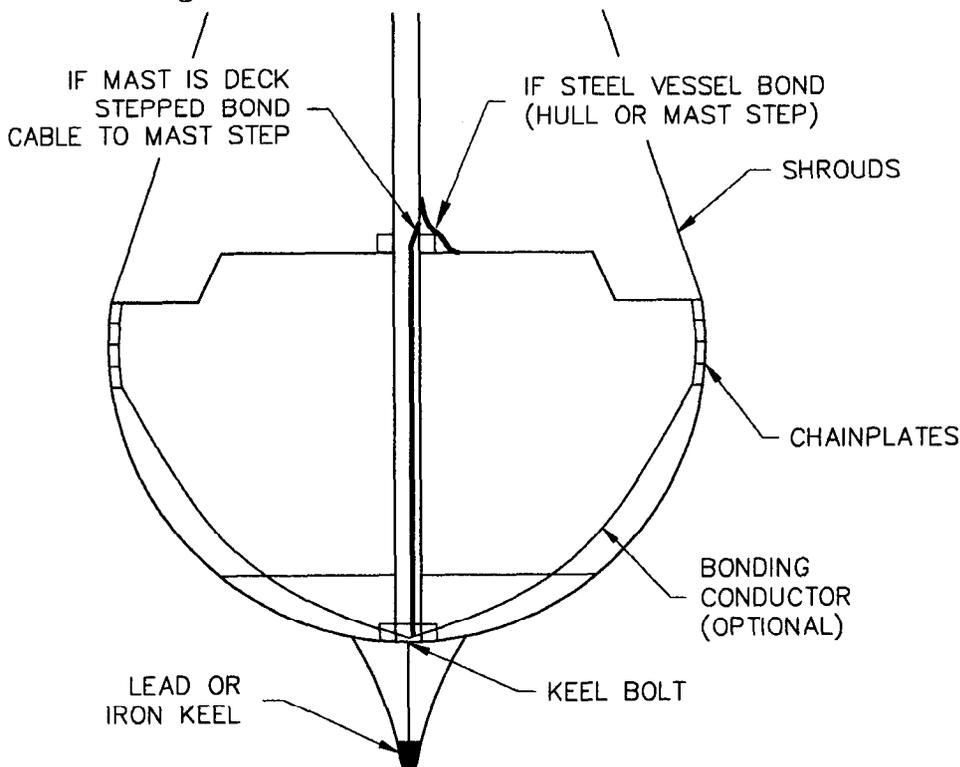


Figure 7-7. Mast Grounding Arrangements.