Grounding concepts for a marine lightning protection system

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1. Scope

The scope of this document is to introduce the major concepts governing sideflash formation and mitigation in the design of a marine grounding system. Physical principles involving potential, electric field, potential equalization, and sideflash formation are described. These principles are then applied to the layout of grounding electrodes, main conductors, and bonding conductors in a marine grounding system.

2. Terminology

2.1. Water terminal – a conducting fitting that acts as a conduit for the lightning current to pass to the water

This term parallels the definition of an "air terminal" at the top of the lightning protection system. While an air terminal is the interface between the lightning and the lightning protection system – acting as an initiation point for the attachment streamer – a water terminal provides an exit point to the water.

2.2. Grounding – the process whereby current flows from a water terminal towards or into the water.

When a conductor is placed in the water to act as an exit terminal for the lightning current, it is common practice is to refer to it as a "ground plate". However, this is a misnomer as the voltage of any water terminal actually that of the whole lightning protection system, which is significantly different from zero volts. Instead, the term "grounding" is preferable to indicate the flow of current into the ground medium (water), rather than a point on an equipotential at ground potential. One corollary to this is that a conductor does not need to be immersed in the water to deliver current into the water. In fact, a conductor in the lightning protection system can act as a water terminal if sparks form from it, and there are cases when a down conductor, a mast base and even a sink drain have inadvertently acted to ground the lightning to water.

2.3. Grounding electrode – a water terminal connected to the lightning protection system

Rather than defining an exit terminal that is attached to the lightning protection system in terms of its shape, such as a "ground plate" or "ground strip", a more descriptive term is "electrode" to reflect its particular function as a terminal through which current flows.

2.4. Sideflash – any discharge occurring during a lightning strike that involves the formation of a spark channel from any source other than an air terminal or a grounding electrode

Sideflashes typically involve conductors on the boat, that may include water tanks and crew members. We distinguish between two types of sideflashes:

2.4.1. Internal sideflash – a sideflash that forms between two conductors on the boat

2.4.2. External sideflash – a sideflash that forms between an on-board conductor and the water.

2.5. Main conductor - tinned copper conductor of at least 2AWG used in the lightning protection system wherever current flow is expected to be generally towards the water

2.6. Bonding conductor – tinned copper conductor of at least 6AWG used in the lightning protection system for potential equalization where orientation is generally parallel to the water surface or location is inside protective zones afforded by main conductors

3. Lightning mechanism

From a yacht's point of view, the lightning strike begins when current flows from any part of the lightning protection system. This is typically tens of milliseconds after the lightning has started in the cloud. Specifically, after a column of charge has been lowered to within a few tens of meters of ground, in a process called the stepped leader, current flows off the top of the lightning protection system up towards the stepped leader in a process termed the attachment streamer. This current either charges the lightning protection system or is accompanied by a current flow into the water, or both. Current flows either from electronic conduction inside conductors or in the form of propagating charged streamers following ionization of air or water and probably totals some hundreds of amperes. Eventually the attachment streamer connects with the stepped leader to form a physical attachment to the boat. At this stage the thundercloud is effectively shorted to ground by a continuous ionized channel, and the peak current follows, with an amplitude of several tens of kilamperes with a rise time of about 100ns during the return stroke phase. This peak current decays in a few tens of microseconds but may be followed by a lower level continuing current (~few hundred amperes) for perhaps several hundred milliseconds. While at a much lower level, the continuing current is the process responsible for the largest heating effects. For a more detailed discussion of all of the processes in a lightning strike, refer to http://www.marinelightning.com/science.htm#Background .

4. Physical concepts

4.1. Potential

4.1.1. Definition

Potential is the energy per unit charge. The lightning protection system becomes charged, usually through the air terminal, by either a direct flow of charge from the lightning channel or by an induced flow of charge into the surrounding air when there is no direct connection to the channel. In either event it becomes energized. As the lightning protection system discharges, this energy is converted into various forms such as heat, electromagnetic, light, and sound, usually in high-power bursts that can do considerable damage, both mechanical and electrical. At any instant the total charge on the lightning protection system is the difference between the charge that has flowed into the air, usually off the air terminal, and that which has been conducted into the water. Whenever there is excess charge on the lightning protection system, the system is energized, and its potential is raised above ground (see Section 4.1.4).

4.1.2. Ground

Potential is the same as voltage, both being represented by "V". Unlike a two-dimensional electric circuit where the voltage can be defined relative to some well-defined "ground" wire or plane, a boat consists of a complicated three-dimensional system of conductors, some of which are connected, that is sitting on another conductor, the water, and nothing can be regarded as being at "ground" potential. In this respect, a boat being struck by lightning should be regarded in the same manner as a system with a positive ground, corresponding to the lightning protection system, where the negative terminal is far from the boat. The fact that ground potential cannot be reached is actually not a problem since the major concern in practice is the potential gradient, or rate of change of potential with distance.

4.1.3. Equipotentials

If the potential of the lightning protection system is V_0, and we assume that the potential is zero far from the boat, then at a particular point in between the potential has an intermediate value. A region or surface where the potential has the same value is termed an equipotential. This is the case inside and on the surface of a conductor. Close to a conductor, the equipotentials are surfaces that have a similar shape to the surface of the conductor. For example, the lightning protection system and all conductors connected to it approximate an equipotential region at potential V_0. If the lightning protection system consists of one long cylindrical down conductor, then the equipotential surfaces are also cylindrical as shown in Figure 4-1. The potential at any point on an equipotential surface is at the potential of that surface. For example, the point shown in Figure 4-1 is at the potential V1, where V0 > V1 > 0.

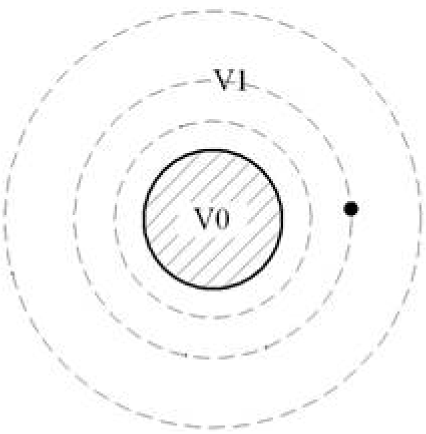

Figure 4-1 Equipotential surfaces around cylindrical conductor

If a very thin conductor with no excess charge is now inserted parallel to the down conductor at the point shown in Figure 4-1, it does not change the situation so that its potential is equal to that of the equipotential surface that it lies on, V1, and the shapes of the equipotential surfaces are the same as before. However, if the uncharged conductor is not very thin, the shapes of all of the equipotential surfaces are changed to satisfy the condition that the conductor surface is also an equipotential, as shown in Figure 4-2. This distorts the shapes of all the equipotential surfaces. While the actual potential of the conductor may still be close to V1, the equipotentials between the conductor and the cylindrical conductor are compressed so that the potential gradient is increased in this region.

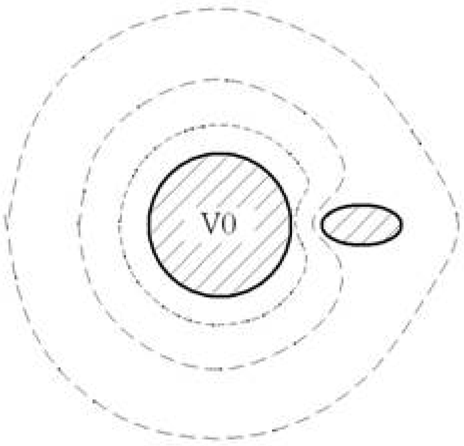

Figure 4-2 Equipotential surfaces around cylindrical conductor in vicinity of isolated conductor

4.2. Electric field

4.2.1. Relation to potential

The equipotential lines on a two-dimensional plot such as in the above figures are analogous to contours on a topographical map. Where contours are more closely spaced, the gradient of the land is steeper. Also, an object falling down a slope moves across the contours at right angles. The electric field represents the gradient of the equipotentials and also crosses each equipotential at a perpendicular. In fact, the electric field is defined as the negative of the potential gradient. Since in three dimensions the equipotentials are surfaces, the electric field is parallel to the normal, where a normal is a vector that is perpendicular to all lines drawn in the surface. In an equipotential region, that is, a volume where the potential is constant, there is no gradient and therefore no electric field. For a perfect conductor the surface is an equipotential so that any electric field is parallel to the normal. Also, the interior volume of a perfect conductor is an equipotential region so that there is no electric field inside. Metallic fittings can be regarded as perfect conductors for virtually all lightning processes.

4.2.2. Electric field in water

When current flows from the lightning protection system into the water through a grounding electrode, a current density field is established in the water. The shape of this depends on the geometry of the electrode, the hull/water boundary, and the injected current from other electrodes. In contrast to metallic fittings, a significant electric field accompanies this current flow so that the surface of the water is not necessarily an equipotential surface. A reasonable approximation for this relationship is $\mathbf{J} = \sigma\mathbf{E}$ where **J** is the current density (in A/m^2), σ is the conductivity (in mho/m), and **E** the electric field (in V/m). The magnitude of the current density depends only on the current provided by the lightning, not the ground impedance. Since fresh water has about 1/100 the conductivity of salt water, electric fields, and hence voltages, are much larger in fresh water. This electric field (or voltage gradient) is fundamental to the problem of sideflash initiation which is thus much more of a problem in freshwater than salt.

4.2.3. Breakdown electric field

At a high enough value of the electric field (about 10^7V/m), the forces on individual air (or water) molecules become high enough to separate out electrons that are then free to move in the general direction of the electric field. That is, the air becomes a conductor and a spark is formed, usually from the surface of a conductor in a perpendicular direction. Where the spark is most likely to start can hence be deduced from a plot of the equipotential surfaces by noting where the equipotentials are most closely spaced. While a complete quantitative analysis is best, much insight can be obtained from simple sketches. For example, in the situation shown in Figure 4-1 and Figure 4-2 the introduction of the finite conductor results in a larger electric field at its inner and outer extremities. If either, or both, of these exceed the breakdown field, sideflash initiation is likely.

In a more practical example, consider the case of the water tank shown in Figure 4-3. The tank is near a lightning conductor and grounding electrode that are at a potential V_0 The current density in the water (ground medium) is assumed radial so that the equipotential surfaces are hemispherical as shown. Since the water in the tank is conducting, the equipotential surface on the tank surface is the same shape as the tank. The corners of the tank compress the equipotential surfaces just outside it and result in a local enhancement of the electric field. As a consequence the inside upper corner is likely to form a sideflash to the lightning conductor, and the outside lower corner to the water.

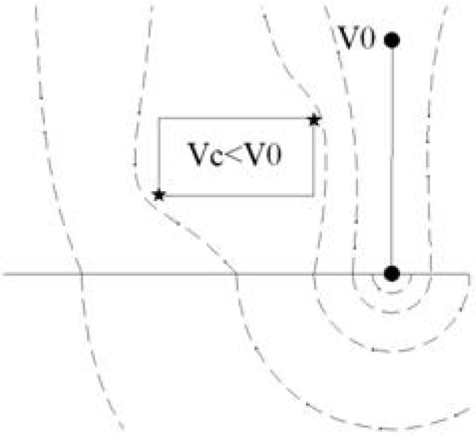

Figure 4-3 Equipotentials and probable sparking points on water tank

4.3. Potential equalization

4.3.1. Bonding

One way to eliminate the risk of the sideflash between the tank and the lightning conductor in Figure 4-3 is to connect the two conductors, that is, bond them together so that their potential difference becomes zero and the local electric field is close to zero. By equalizing the potentials of the two conductors the region between them is thus much less hazardous to crew members in this vicinity. However, the bonding connector now changes the potential distribution in that the tank is now at the same potential as the down conductor, as shown in Figure 4-4. The equipotentials become more concentrated on the outer edge of the conductor and so increase the risk of a sideflash from this edge, as shown in Figure 4-4. This risk is magnified if the conductor is close to the water.

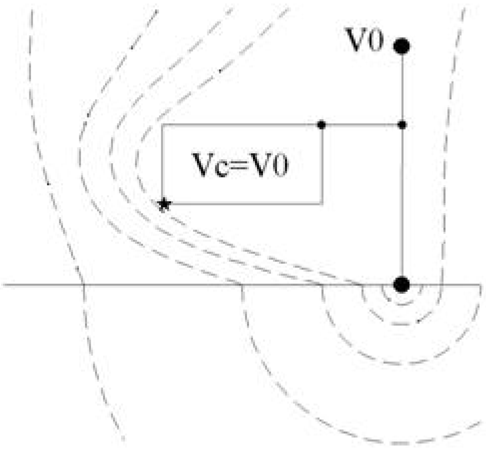

Figure 4-4 Equipotential surfaces near conductor bonded to down conductor

4.3.2. Shielding

Another technique for equalizing potentials is shielding. This is based on the principle that no electric field exists inside a volume surrounded by a closed equipotential surface as long as each conductor inside the volume is uncharged. Since electric field represents a changing potential with distance, a zero electric field implies a constant potential, that is, the whole volume is an equipotential region. The most common method to ensure that an equipotential surrounds a region is to use a conductor surface to provide the equipotential surface and region, that is, to construct a Faraday cage. The conductor to be protected should be inside the shielding conductor, with the lightning down conductor outside. The down conductor may be either bonded or not, depending on the relative sideflash hazards discussed above. This technique works well for small portable instruments. However, the increased sideflash risk from the lower corners of the Faraday cage means that this technique cannot be used near the water.

4.3.3. Grounding

While it is straightforward to simulate the top three sides of a Faraday cage with down conductors, the bottom of the cage needs to be in the water to avoid sideflashes as noted above. In fact, if a long grounding electrode is immersed in the water directly below the conductor the risk of a sideflash from the bottom of the conductor is effectively eliminated, as shown in Figure 4-5. Since the vast majority of sideflashes propagate towards the water, the shapes of grounding electrodes are more important than the down conductors above the conductor

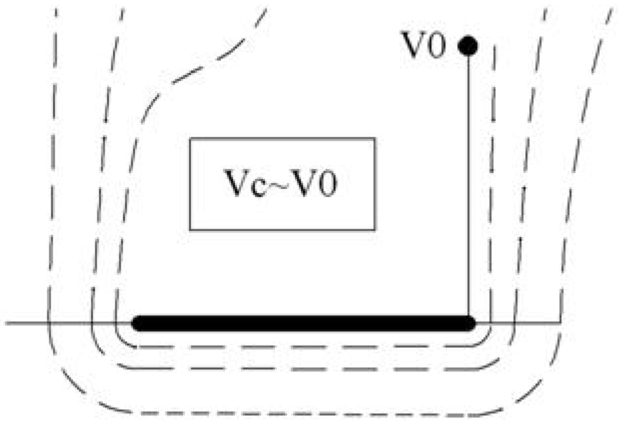

Figure 4-5 Strip grounding electrode below unbonded conductor

However, it is impractical to construct a network of grounding strip electrodes, which is what is needed to give effective shielding in three dimensions. An alternative technique is to surround the conductor at risk with point electrodes that inject current into the water in such a pattern as to reduce voltage gradients in the vicinity of the conductor's corners. That is, the electrodes reduce the potential difference between the corners of the conductor and the water nearby, as shown in Figure 4-6.

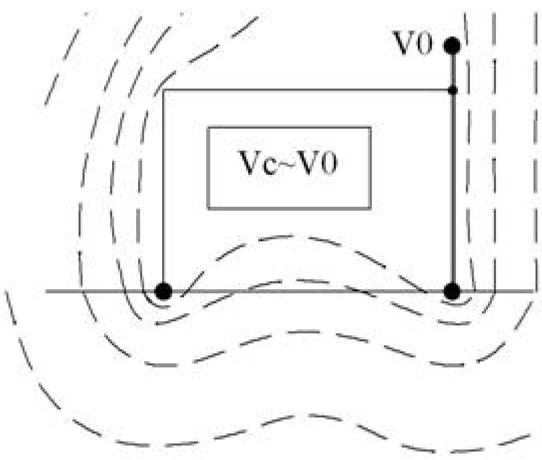

Figure 4-6 Point electrodes below unbonded conductor

Note that in both Figure 4-5 and Figure 4-6 the potential of the conductor is close to that of the lightning protection system even though the two are not bonded so that the risk of a sideflash between the down conductor and the conductor is virtually eliminated.

5. Theory for sideflash initiation

5.1. Quasi-static field model

Consider a simple model where current *i(t)* is flowing into a lightning protection system comprising an immersed grounding electrode and a single conducting fitting that is bonded to the system. The potential of the whole system is *v(t),* where ground potential is an infinite distance away. Conduction current flows from the grounding electrode into the water and gives rise to a current density *j(t)* in the water. Charge buildup on the conducting fitting gives rise to an electric field $E_c(t)$ which has a maximum value at same point on the fitting of $E_{max}(t)$. The situation is illustrated in Figure 5-1.

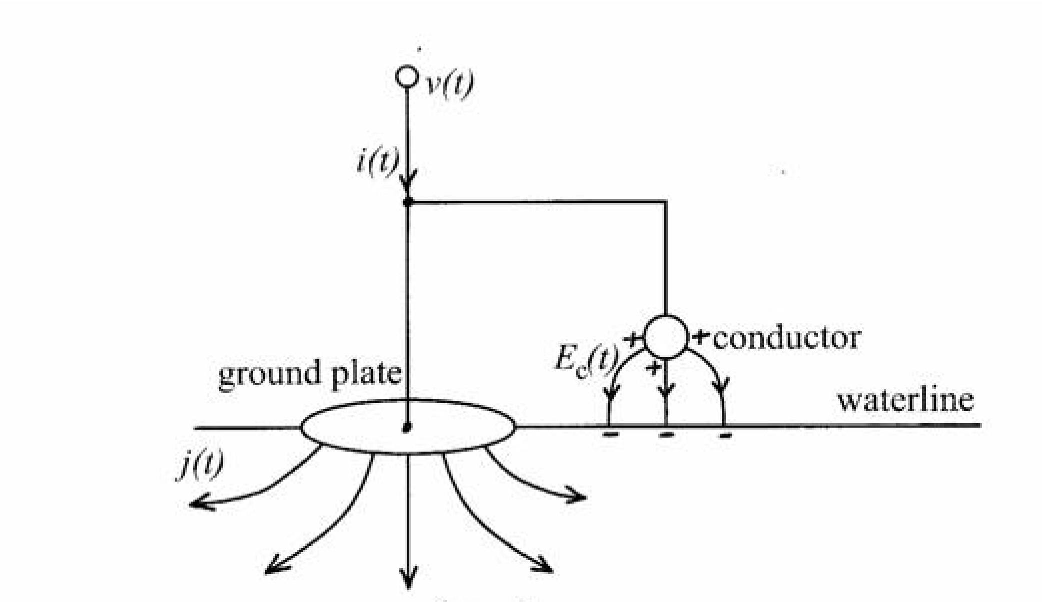

Figure 5-1 Model for field prediction

If we assume that the dimensions are much smaller than a wavelength, then both the current density and electric fields are quasi-static and electrostatic concepts can be applied. In this case the electric field at a particular point is proportional to the voltage, and, in particular,

$$E_{max}(t) = \left(E_{max}/V\right) v(t)$$

where the constant of proportionality (E_{max}/V) is a geometrical factor. Electrical breakdown occurs if $E_{max}(t)$ exceeds the critical field strength, about 10^7 V/m in air. It is useful to express this factor in terms of an equivalent distance, d_{eff} where

$$d_{eff} = \left(E_{max}/V\right)^{-1}$$

5.2. deff versus conductor geometry

The potential field from a charged conducting fitting raised to a potential V_0 in the vicinity of a ground plane can be found by solving La Place's equation in the region between the ground plane and the conductor by using the method of images. This has already been down for several simple geometries:-

(i) long cylindrical rod perpendicular to the ground plane

(ii) sphere
(iii) long cylinder parallel to the plane
(iv) infinite plate parallel to the ground plane.
These geometries are illustrated in Figure 5-2.

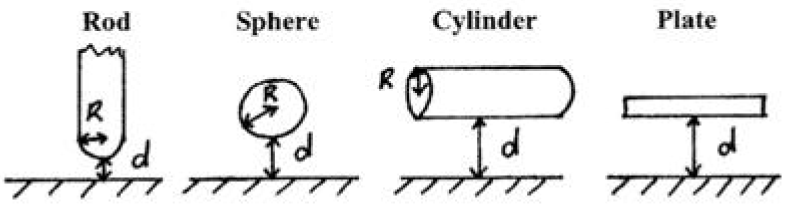

Figure 5-2 Conductor geometries

Once the solution for the potential field has been found, the electric field is calculated as

$$\mathbf{E} = -\Delta V$$

and the point on the conductor can be determined where **E** has a maximum value, which is generally at the closest point to the ground plane. If the value of the electric field at this point is E_0 then

$$d_{eff} = \left(E_0 / V_0\right)^{-1}$$

Figure 5-3 shows this factor in a dimensionless form of d_{eff}/d versus R/d on a semilog scale. The additional plot of $d_{eff} = R$ is included to demonstrate that the effective distance is equal to the radius for both a sphere and perpendicular rod if d>>R, that is, the conductor is many radii above the ground plane. Note that d_{eff} for a perpendicular rod is about an order of magnitude smaller than that for a parallel rod of the same size and spacing, while d_{eff} for a plate is much larger than that for both rod and cylinder for d>>R, approaches the rod but becomes smaller than the cylinder for d<<R (conductor close to ground plane).

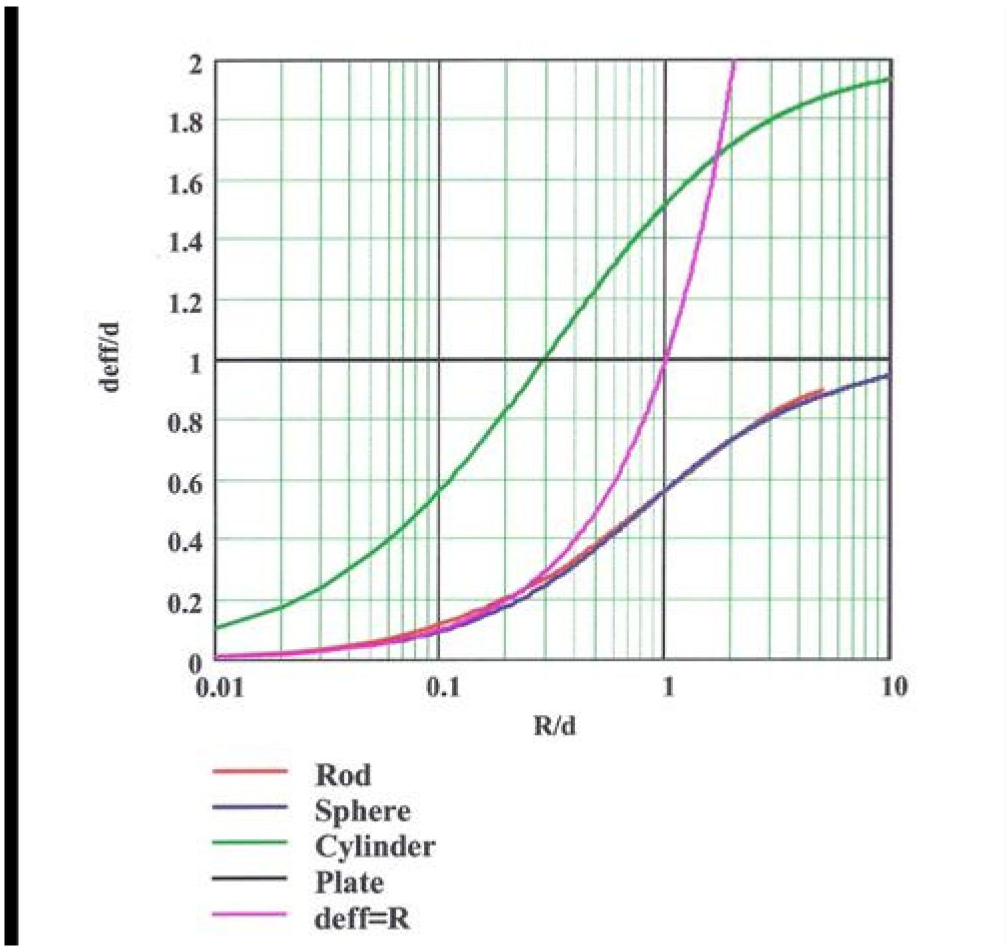

Figure 5-3 Geometrical factors for conductor shapes

5.3. Circuit equivalent

The equivalent circuit corresponding to Figure 5-1 is shown in Figure 5-4.

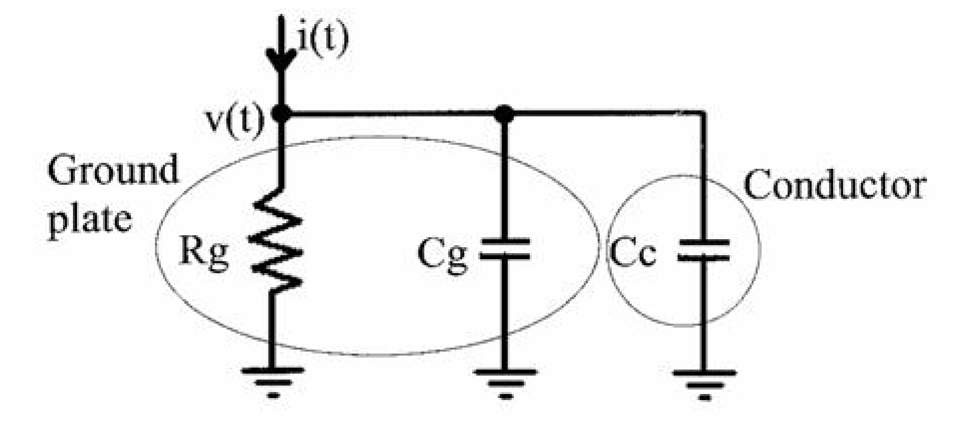

Figure 5-4 Equivalent circuit

R_g is the resistance of the grounding electrode and C_g is its capacitance, both with respect to a ground potential at infinity. These are related by

$$R_g C_g = \tau$$

where

$$\tau = \varepsilon / \sigma$$

is the relaxation time of the water, ε is the permittivity of the water and σ the water's conductivity. For salt water τ is less than a nanosecond, while in fresh water, τ is about a microsecond. With rare exceptions (for example, a large SSB ground plate) the capacitance of a conducting fitting is much smaller than C_g. Since the lightning current splits between the grounding electrode and the fitting, continuity of current gives

$$i(t) = \frac{v(t)}{R_g} + (C_g + C)_c \frac{dv(t)}{dt}$$

where the first term in is the conduction current and the second term the displacement current. Two situations are of interest: t>> τ, when conduction current determines the voltage, and R_g=, when charge accumulation dominates the voltage.

5.3.1. Current dominant regime, t>> τ

In this case the conduction current predominates, that is the situation is ohmic. This corresponds to the usual interpretation for lightning grounding. Terms such as "ground resistance" and "step potential" imply this linear and in-phase relationship between voltage and current. Since the relaxation times in water are smaller than the characteristic time scales of most lightning processes, the exception being the rise time of subsequent strokes, it is a reasonable assumption if volume currents are flowing into the water

In this case ground resistance can be calculated for various geometries of grounding electrode. Table 1 gives the ground resistance and peak voltage expected for a 30kA return stroke current.

Electrode type	Water type	Resistance	Voltage for 30kA return stroke
0.1 m^2 circular plate	Fresh[1]	1.45 kW[3]	44 MV
	Salt[2]	0.36 W[3]	11 kV
9.3 mm x 10m strip	Fresh[1]	235 W[3]	7 MV
	Salt[1]	60 mW[3]	2 kV

[1] Conductivity = 10^{-3} S/m [2] Conductivity = 4 S/m [3] IEEE Trans. EMC, 33, 132-138, 1991

Table 1 Resistance and peak voltage for 30kA current versus electrode shape

Rewriting as

$$E_{max}(t) = v(t) / d_{eff}$$

we can determine a critical value of d_{eff} that results in a breakdown electric field of $3x10^6$ V/m if the potential of the lightning protection system is V_0 from

$$d_{eff} = \frac{V_0}{3x10^6}$$

or, in terms of the current I

$$d_{eff} = \frac{R_g I}{3x10^6}$$

Table 2 gives values of this critical d_{eff} for two lightning processes – an attachment streamer with assumed current of 500A and a return stroke with a peak current of 30kA.

Electrode type	Water type	R_g	Critical d_{eff}	
			Attachment I=500 A	Return stroke I=30 kA
0.1 m^2 circular plate	Fresh[1]	1.45 kW	24 cm	1.5 m
	Salt[2]	0.36 W	61 mm	0.4 mm
9.3mm x 10m strip	Fresh[1]	235 W	4 cm	23 cm
	Salt[2]	60 mW	10 mm	60 mm

Table 2 Critical values of effective distance for attachment streamer and return stroke peak

Since d_{eff} can be generally interpreted as the minimum radius of curvature for a perpendicular fitting that is not close to the waterline, Table 2 indicates whether a fitting is likely to form a sideflash. In the case of a boat in fresh water, even a lightning protection system with the more effective ground strip is likely to initiate sideflashes from almost any fitting. Fittings that are further from the lightning grounding electrode, closer to the water, and with smaller radii of curvature are the ones most likely to breakdown first.

5.3.2. Charge dominant regime, $R_g=\infty$

If a grounding electrode is not in perfect electrical contact with the water, a rise in potential is not accompanied by ohmic conduction current flow since the conduction current is zero. In this case the lightning current flowing in the lightning protection system becomes displacement current out of C_g and C_c and the system voltage, and electric field, is proportional to charge. For the maximum electric field on a conducting fitting

$$E_{max}(t) = \frac{1}{d_{eff} C} \int_{t'=0}^{t} i(t')dt'$$

where C is the total capacitance to ground, and a critical time to reach breakdown, t_{crit}, can be determined. Consider a very conservative case of a large flat plate that is separated from the water by a distance d and assume that breakdown occurs first on the plate surface rather than its edges. For a steady current I_0 the critical time is given by

$$t_{crit} = \frac{K_e \epsilon_0 E_b A}{I_0}$$

where K_e is the relative permittivity, E_b the breakdown electric field, and A the area of the plate. Assuming E_b=3x10^6 V/m and K_e=1, the critical time for a 0.1 m^2 circular plate is only 25 ns for a current of 100 A, corresponding to an underestimate for the attachment streamer. In 25 ns the attachment streamer propagates about 3 cm. However, if there is another conducting fitting with a smaller d_{eff}, this will preferentially breakdown before the plate. That is, in the absence of a conduction current into the water, sideflashes are initiated virtually as soon as the attachment streamer begins.

6. Two case studies

6.1. Common features

The following two case studies demonstrate the ineffectiveness of a single grounding surface. In both cases:
the rigging was grounded to the keel ballast, the grounding area was well in excess of 1ft^2,sideflashes occurred, and the sideflashes blew holes in the hull at the waterline.

6.1.1. Current flow through grounded keel

In this case the bottom of the mast was grounded to a keel bolt. Following a lightning strike, the owner commented that thousands of hole had formed at the surface of the keel ballast. He also observed evidence of arcing at both bow and stern.. At the bow, he concluded that a discharge had formed between the forestay chainplate and a water tank, and then from the water tank to the water at the waterline, leaving a large puncture hole, as shown in **Figure 6-1**. At the stern, the discharge apparently formed from the backstay chainplate, through an aluminum organizer and rope, and then to the water, once again at the waterline leaving a large hole.

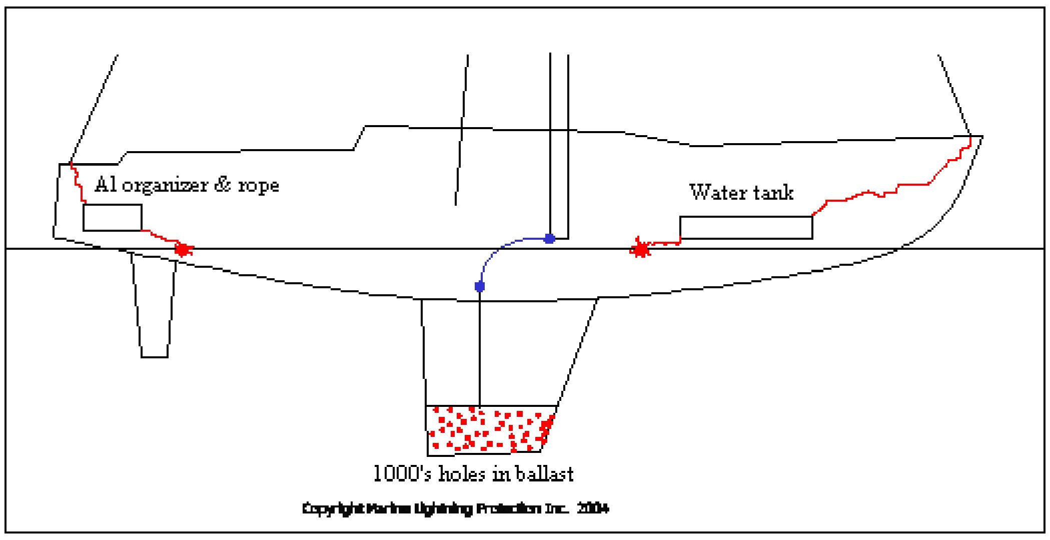

Figure 6-1 Lightning damage to grounded boat in fresh water

There are several interesting features in this case.
(i) The holes in the ballast, indicated that current had flowed out of the keel ballast, which had a much larger area than 1 ft^2.
(ii) The two sideflashes made holes at the waterline. Note that the waterline is the intersection of the hull's outer surface with the surface of the water. That is, the waterline forms an edge that provides a local electric field maximum conducive to discharge initiation.
(iii) The origin of each sideflash was a chainplate at the lower end of a stay, a long narrow conductor that is oriented at right angles to the water surface. d_{eff} for a stay is expected to be of the order of its radius, that is, very small compared to other nearby fittings.
(iv) Both sideflashes connected through intermediate conductors that were electrically isolated from the lightning protection system. This demonstrates the occurrence of both internal and external sideflashes.

In order to provide for adequate protection in this case the following remedies would be useful:
(i) Additional grounding electrodes in the general vicinity of the backstay/organizer and forestay/water tank would provide alternative grounding paths for the discharge that formed from the forestay and backstay.
(ii) Electrodes amidships would also be advisable, given that one of the sideflashes punctured the hull in this region.
(iii) The optimum location for all grounding electrodes is at the waterline.
(iv) A bonding connection between the lightning protection system and the aft organizer would equalize the potential between these and eliminate the risk of an internal sideflash. Note however that, in the absence of additional external lightning conductors and grounding electrodes, this bonding connection also increases the risk of an external sideflash.
(v) Potential equalization is also required for the water tank. However, for a plastic or fiberglass tank, bonding connections are impossible. Instead, a preferable technique would be to employ the concept of shielding by using external conductors and ground current injection as illustrated in Figure 4-6.

6.1.2. Current flow avoiding grounded ballast

As in the above case, the lead ballast here also was connected to the rigging, but this time via down conductors from the side chainplates. While the owner reported similar symptoms of holes at the waterline, there were none at the surface of the ballast. Further, the holes were close to the down conductors connecting the sidestay chainplates to the keel bolt.

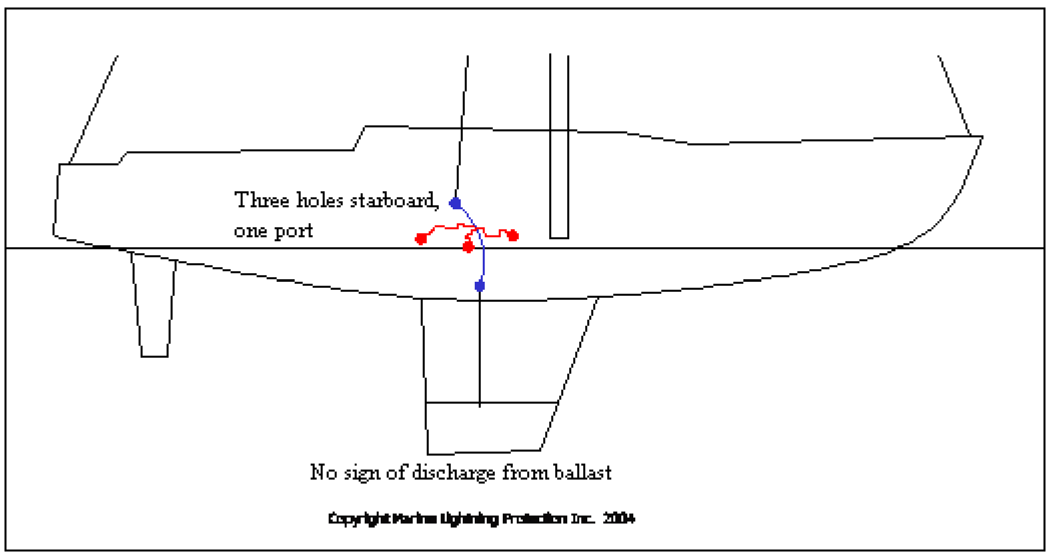

Figure 6-2 Lightning damage to grounded boat in fresh water

Of particular note here were:
(i) There was no indication that current flowed out of the keel. The keel was painted but not encapsulated in fiberglass.
(ii) The sources of the apparent sideflashes were the down conductors from the two sidestay chainplates.
(iii) The holes once again were at the waterline.

To remedy the sideflash hazards in this case would require additional grounding electrodes near the waterline and outside the down conductors

7. Application to lightning protection

7.1. Objectives

The primary objective for a lightning protection system should be to minimize electric fields inside the boat so that both sideflash risk and the hazard of high potential differences are reduced. Some specific techniques that address this main objective are:
(i) Layout of lightning conductors near the outer surface of the hull;
(ii) Extensive bonding of conducting fittings to the lightning protection system;
(ii) Incorporation of multiple grounding electrodes near conducting fittings that are susceptible to sideflashes;
(iii) Optimization of grounding electrode design to maximize effective contact area with the water at the time of the peak lightning current.

7.2. Sideflash hazards

The calculations in Section 5 predict that sideflashes are inevitable in fresh water, are initiated preferentially from conducting fittings with small d_{eff} , and occur almost simultaneously with the start of the attachment streamer if there is no conductive connection with the water. Applying these ideas to the conducting fittings on a boat, we can identify particular fittings that are at relatively high risk. Consider a simple sailboat hull with mast, forestay, back stay, sidestays, and a water tank as shown in Figure 7-1.

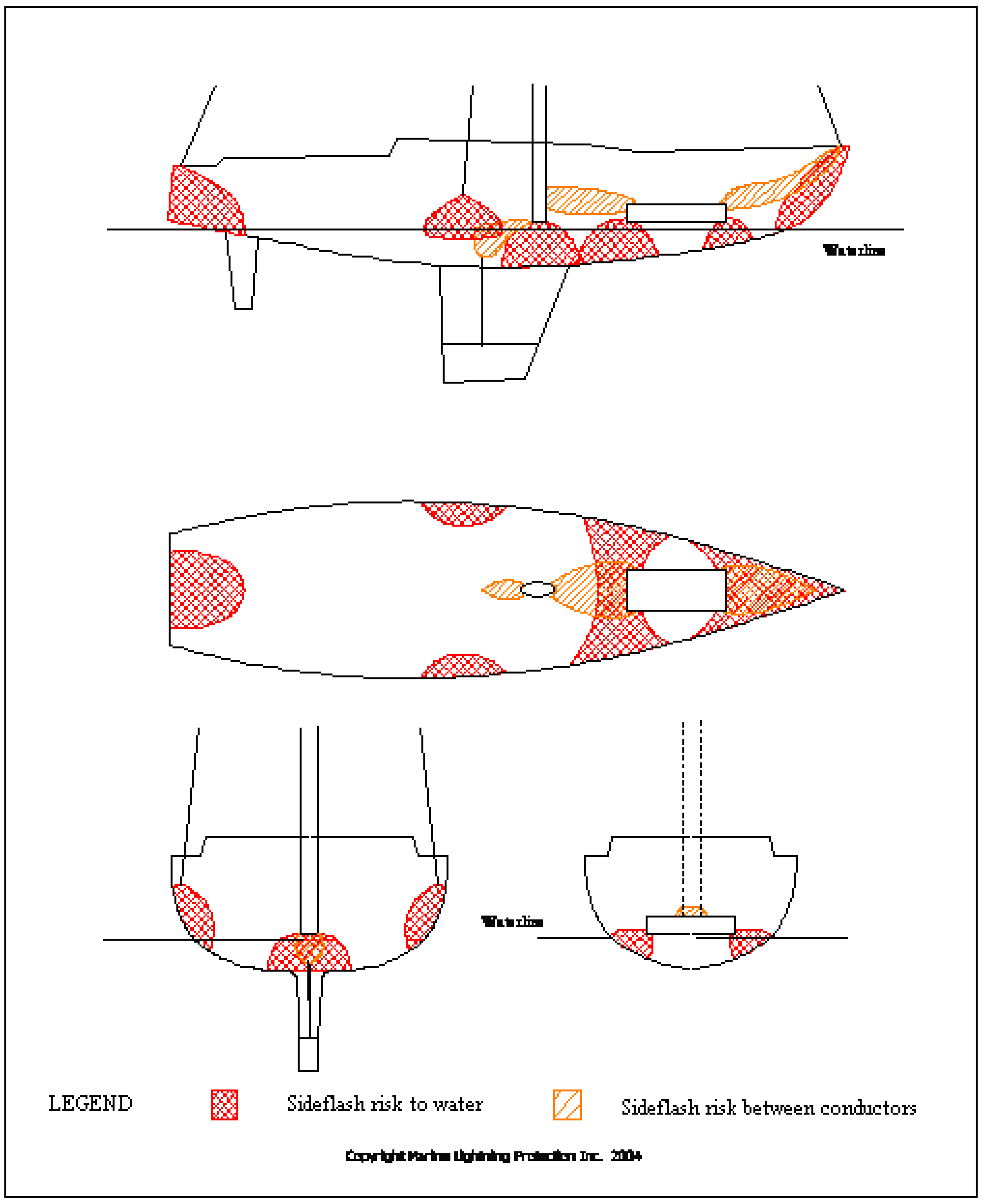

Figure 7-1 Regions of high sideflash risk

In practice, a sailboat has many more conducting fittings near the waterline so that in practice the region of sideflash risk would encompass effectively the whole volume near and below the waterline. In a powerboat the problem is even more pervasive.

7.3. Layout for lightning conductors and grounding electrodes

Given the sideflash hazards illustrated in Figure 7-1, the lightning conductors and grounding electrodes should be placed to approximate an equipotential region inside the boat, that is, to equalize potentials as explained in Section 1.9. In general, this means to bond metallic fittings, place lightning conductors around vulnerable regions, use existing immersed metallic fittings as grounding surfaces, and inject current into the water near conductors that are close to the waterline or the water. Figure 7-2 shows a possible layout to reduce the sideflash hazards in Figure 7-1 The lead ballast is utilized for immersed area and additional sparking electrodes are added at the extremities of all main conductors that encircle the water tank and crewed area inside the cabin. The major bonding/interconnecting conductor forms a ring around the hull at deck level to minimize the risk of a sideflash from other than the grounding electrodes.

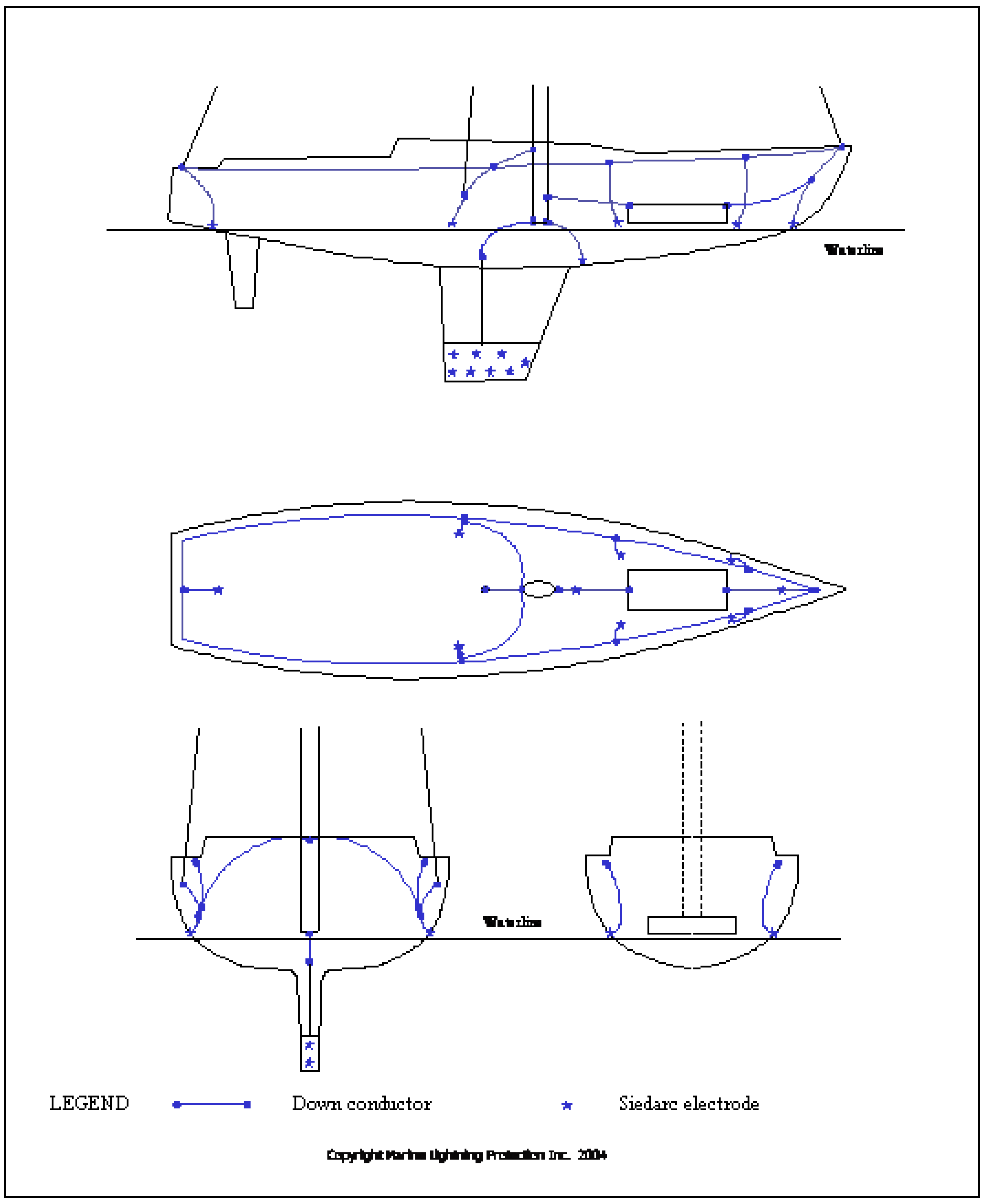

Figure 7-2 Conductor and grounding electrode layout

7.4. Design of sparking electrodes

The results of Section 5 can also be utilized in the design of a lightning grounding system. If an additional grounding electrode is placed in the vicinity of a vulnerable fitting, it provides a bypass path. The current injected into the water at this point gives rise to a localized equipotential region in the water (see Figure 4-6) that, in combination with the connected lightning conductor, tends to shield other fittings inside. Multiple grounding paths (a) divide the lightning current, thence lowering overall ground impedance, and; (b) distribute it over the hull surface, thereby decreasing electric fields in the water to further lower sideflash risk. While electrodes that are in contact with the water are suitable for this purpose, there are many reasons why they are both impractical and undesirable. Alternatively. an electrode that is designed to initiate a spark, in a similar manner to an air terminal, is capable of forming a conductive path between the lightning protection system and the water to satisfy the above conditions.

Some desirable attributes for electrodes whose primary function is to promote a spark are:
(i) Meet NFPA standards for an air terminal to allow for the heating at the spark/conductor interface;
(ii) Perpendicular orientation to hull.
(iii) Preferably mounted above waterline to avoid possible interaction with water in the hull laminate.
(iv) Shaped to promote initial current flow, that is, having small d_{eff}

8. Summary

As the interface between the water and the lightning protection system, the grounding system provides discharge paths for the lightning charge. The main function of the grounding system is to prevent sideflashes, both from conducting fittings to the water and between conducting fittings. In order to perform this function, multiple exit terminals are required and current flow into the water is maximized, especially at the time of peak current, to limit the voltage of the lightning protection system. Layout of lightning conductors and grounding electrodes takes account of conducting fittings that are at high risk of forming sideflashes and vulnerable regions of the boat such as crewed areas and sites of electronics equipment. The use of sparking electrodes enables grounding paths to be established in locations where immersed electrodes are impractical.

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