Analysis of Lightning and Surge Protection for Float Ground System

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***Abstract*— Lightning and power surges are phenomena where the over spike occurs for a short period of time. There are few main sources of power surge which are switching, lightning strikes, coupling, electrostatic discharge and nuclear electromagnetic pulses. To minimize the damage due to surge activities, proper installation of grounding system is essential to suppress the surge into the ground. However, there are some systems where physical grounding is not possible such as vehicles, ships and aircraft. In the absence of a proper lightning protection system, direct lightning strikes can cause lethal accidents in vehicles, particularly in aircraft and ships. In the current research, the impact of surge and its protection method for float ground systems were investigated. Various test waveforms as specified in different standards are simulated and examined. These surges can be modeled according to the IEC standard 1.2/50µs opened-circuit voltage and 8/20µs shorted-circuit current waveform.**

Keywords— Lightning and Surge Protection, Float Ground System, Surge Generator, Surge Protection Devices, CST Simulation

I. INTRODUCTION

A power surge is a temporary spike or transient overvoltage and overcurrent that can be found in electrical or electronic circuits. Lightning, switching on/off of motors, magnetic and inductive coupling, as well as electrostatic discharge, are few causes of power surge. Although it only appears for a short duration, typically in microseconds, its effects can range from minor damage such as degradation of circuitry to severe damage such as permanent failure of equipment. Proper grounding method is vital for protection against surge and lightning thereby minimizing damages. Permanent damage of equipment can lead to catastrophic accidents in vehicles especially aircraft, watercraft and spacecraft. The increased use of solid-state electronics and integrated circuits that are more susceptible to interference in automobile, marine and aviation industry have made their system more vulnerable to a power surge. Therefore, surge protection is very important in electrical and electronic systems. Some effects of direct lightning on vehicles include melt through of metal surface, burning of wires and ignition of fuel [1].

As technology advances, the number of solid-state devices and integrated circuits such as microprocessors used in the control and operation of vehicles increases. Most of these devices are sensitive and vulnerable to lightning and power surge. With the increased sensitivity of the equipment, the need for protection against transient overvoltage or overcurrent in the vehicle's electrical and electronic system becomes vital as fail of equipment may result in great losses and fatality. Most lightning strikes experienced by an aircraft are self-initiated by the aircraft. This initiation process happens most frequently during climbing and landing [2]. Besides, a recent study shows that the number of the lightning storm increases in heavily trafficked ship lanes due to the particles from ship exhaust [3].

II. SOURCES OF POWER SURGE AND ITS WAVE PATTERNS

In general, a surge is a transient wave of current, voltage or power in an electric circuit. The external surge includes lightning and utility grid switching, while the internal surge is generated when switching the power on and off. Switching surge is the most common surge that happens in both intended and unintended daily operations of an electrical system. Despite the high frequency of occurrence, normally, the effect of switching surge is less obvious and not disruptive.

Lightning charges are results of the collision between soft hail particles and small crystals of ice that causes a charge separation process where positive charges accumulate at the top and negative charges at the bottom of the cloud. The process of the main charge formation of a cloud is shown in Figure 1. Electrical discharge happens when the built-up charges are enough to break the air insulation [2].

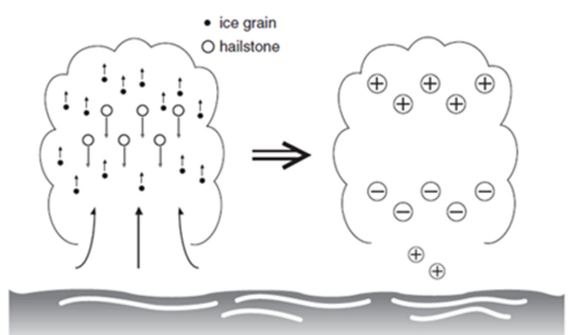

Figure 1: Charge formation in a cloud

A lightning strikes can be classified as cloud to ground strike, inter-cloud strike, intra-cloud strike and cloud to the airstrike. Cloud to the ground is usually the main concern in a lightning protection system. Cloud to ground lightning can be further broken down into four categories, namely positive and negative upward initiated as well as positive and negative downward initiated as shown in Figure 2 [2].

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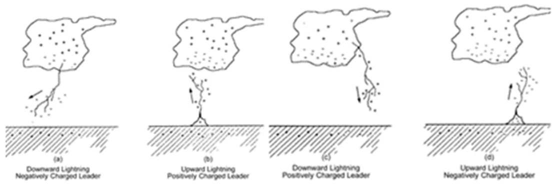

Figure 2: Four types of cloud to ground lightning strikes

A standard surge waveform is characterized by its front time, T_f which is the time to reach its peak value and the tail time, T_t represents the time required to decay from its peak value to half of the peak value. For example, a 1.2/50 µs surge means that the surge has 1.2 µs T_f and 50 µs T_t. The typical waveform of a surge is shown in Figure 3 [4]. Table 1 lists down few common standard surge waveforms and the source of the surge.

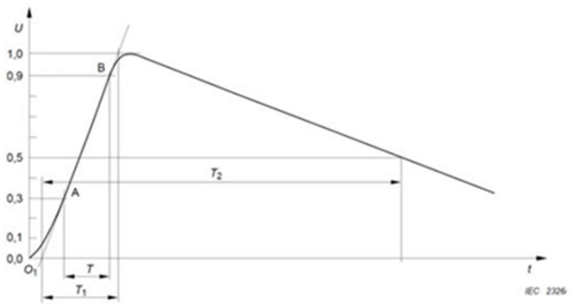

Figure 3: Typical surge waveform

Table 1: Standard surge waveforms

Waveform / µs	Source
1.2/50	Lightning voltage
8/20	Indirect lightning current
10/350	Direct lightning current
250/2500	Switching voltage
250/1500	Switching voltage

III. Floating Ground Systems

Float ground systems are defined as systems that do not have a physical electrical connection to the Earth. Since vehicles are mobile, airplanes and ships, are not meant to operate on land, the actual connection with Earth is nearly impossible for most of the time and is said to be 'floating'. It is important that vehicles' electrical/electronic system has a proper grounding method to provide a path for the dissipation of lightning energy.

A. *Protection against Lightning and Power Surges*

Lightning protection of a float ground system can be protected by using a Faraday cage, which is a closed metal case surrounding a piece of equipment or system, with appropriate thickness and no apertures in the wall. According to the electromagnetic field theory, with sufficient thickness of metal cage, the electric current and electromagnetic field experienced by the system inside the cage is almost negligible. However, there is no perfect Faraday's cage as there will always be some openings for purposes such as windows, doors and antennas. To counter this problem, a topological shielding method that combined the concept of the Faraday cage and the use of surge protective devices (SPDs) is developed. In this approach, the Faraday cage will divert the lightning current away while SPDs will limit the voltage and current on power and communication lines. All conductive body or frame of vehicles is an approximation of a Faraday's cage or the case of topological shielding. When lightning strikes the metallic case of a vehicle, the lightning current will not enter the interior of the vehicle, instead, it will just flow through the metal surface and dissipates through the grounding system either to the air, sea or earth [2]. Figure 8 shows the graphical explanation of this situation when lightning hits a MRT [5].

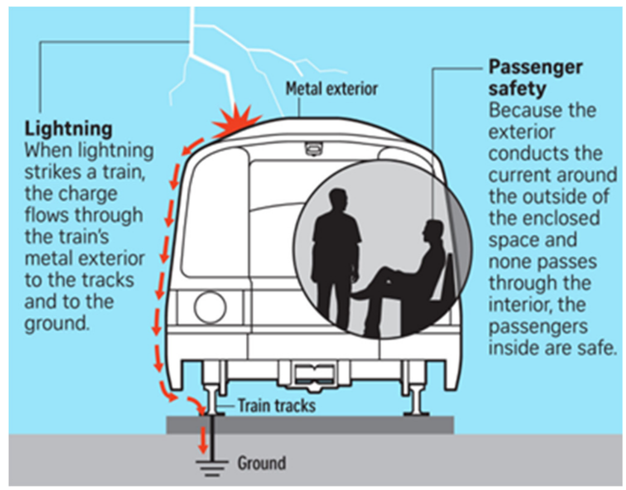

Figure 8: When lightning strikes a train

B. *Protection for Sea Electronic Systems*

Metal ships are generally less threatened by lightning strikes as its frame that approximates a Faraday cage provides lightning protection and the lightning current can be dissipated quickly into the ocean through the metallic hull. With the increased use of fibreglass and rubber coated parts to make the ship lighter and conceal electromagnetic field, the continuity of electric current to hull has been disrupted and the ship becomes more vulnerable to lightning strikes. External lightning protection is therefore needed which is also recommended for a metallic ship for extra protection. Air terminals and down conductor that is connected to the ground plane can be installed for lightning protection. The height and location of air terminals can be determined using methods such as the rolling sphere, cone of protection, elliptical and statistical method. Aluminium mast on ships with sufficient height can be used as the air terminals and down conductor as long as the electrical continuity with the hull is maintained. Engines that often grounded to shaft and propeller should be grounded directly to the ground plate to avoid damage from lightning current flows in the bearings.

Besides SPDs, it is suggested that an active power surge compensator (APSC) which consists of an inverter and energy storage device can be used to prevent the damage of transient voltage and current. When transients occur, the power will be supplied from the storage device of APSC which is charged when there is a power surplus from the generator. This transfer of energy stabilizes the electrical system [6].

C. Protection for Air Electronic Systems

Copper or aluminium mesh is used for lightning protection in composite aircraft to reduce the structure's surface resistance so that the lightning current can be spread over the path. Besides metallic mesh, metallic expanded foils, woven fibre fabric, metal coating, conductive paint and epoxy resin are a few other methods to increase the surface conductivity of an aircraft [7]. For random protection, diverter strips are used to divert the lightning current away. Segmented diverter strips ensure antenna communication [8].

Precipitate static (P-static) is formed through the contact of aircraft with particles in the air. The discharge of P-static creates a magnetic wave which leads to signal interference. A static discharger installed on an aircraft reduces the static discharge threshold so that the amount of static charge on the aircraft is reduced [9].

D. Protection for Land Electronic Systems

Unlike automobiles with a fully enclosed metal frame, convertibles, open-framed vehicles and vehicles with non-metallic frame does not provide protection from lightning. Hence, it is advised that during a thunderstorm, touching any metallic structure, radio, steering wheel, ignition and gear shifter should be avoided. External protection methods such as Shandun lightning rod and fast-installation earth electrode can be used to improve lightning protection [10].

Since a train can be powered by catenary, ground wires can be employed for lightning protection. Down conductors are needed to connect the ground wires directly to grounding rods. Thunder proof transformer should be installed in the equipment room. Besides, the installation of extended mast terminal (EMT) at nearby towers can reduce the potential difference between tower and ground when it is struck by lightning thereby reducing the coupling effect [11].

IV. Damage and Case Studies

There are four specific properties of lightning current which result in its damage ability that is peak current, the maximum rate of change of current, charge transferred and specific energy of the current [2]. When lightning struck, the damage caused can be either direct or indirect. Direct damage includes burn through or melting of metal, deformation of metal due to magnetic force, pitting, resistive heating and ignition of flammable objects such as fuel. Indirect damage to lightning is caused by the induced surge and will have the same effects as surges caused by other sources. Some case studies of the impact of lightning strikes are listed below:

1. In the year 1963, an aircraft Boeing 707-121, the Pan American Flight 214 has crashed and results in 81 deaths. After an investigation, it was found that the plane crashed because of the explosion results from the fuel ignition induced by a lightning strike in reserve fuel tank [2].

2. In 1965, Flight 517, a Convair aircraft experience a lightning strike during take-off. Damages were found in the landing gears, nose wheel, wheel rims, fuselage near the nose wheel, grounding wire and stabilizer cap [2].

3. A ship named Hangjun 12 of Changhang Wuhan Engineering Bureau was struck by lightning in the year 2012. After the strike, weather instruments, electronic information equipment and electrical equipment were damaged [12].

4. In Kanto, Japan, an automobile was burnt as a result of a lightning strike in the year 2013. The car that was burnt in this accident [13].

V. CST Simulation for Float Ground Systems

CST Microwave Studio is used to simulate the electromagnetic environment around the vehicles when it is struck by lightning. The effects of the vehicle's frame conductivity and distance from the frame or mast on the internal surface current, induced a magnetic field and induced current inside a cable are simulated.

Table 2: Conductivity of materials used

Material	Conductivity / S m^{-1}
Copper	5.96×10^7
Aluminium	3.56×10^7
Steel	7.69×10^6
Carbon Fibre Composite (CFC)	(45000, 200, 1.3)

The conductivity of each material is shown in Table 2. It can be seen that the conductivity reduces from copper to CFC. CFC has a different conductivity in a different direction. Is it said to be anisotropic and the mechanical strength varies with direction. To increase the structural properties of CFC use in the aerospace industry, layers of CFC are arranged in a quasi-isotropic layup as shown in Figure 10. Quasi-isotropic material layup can be modeled using the thin panel function of CST.

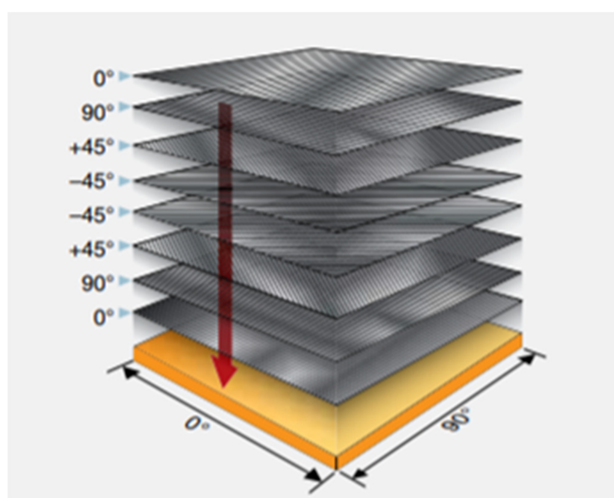

Figure 10: Quasi-isotropic material layup

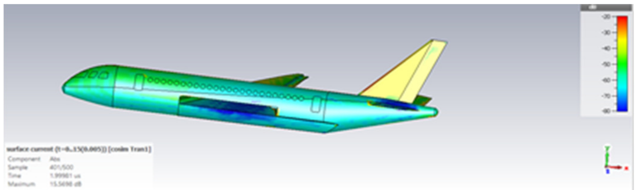

Figure 11: Surface current – Aircraft with no windows (Aluminium frame)

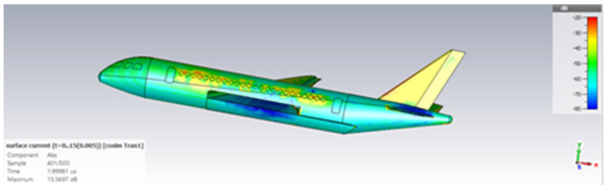

Figure 12: Surface current - Aircraft (Aluminium frame)

When comparing Figure 11 and Figure 12, it can be seen that the overall surface current is similar except for the area near the windows which has a higher surface current. This shows the effects of having apertures or openings such as windows for aircraft on the effectiveness of lightning protection.

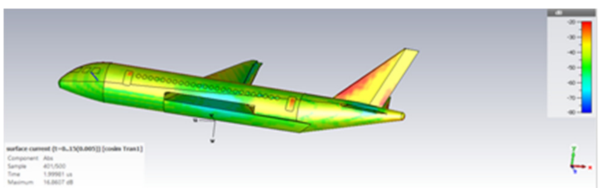

Figure 13: Surface current - Aircraft (CFC frame with copper mesh)

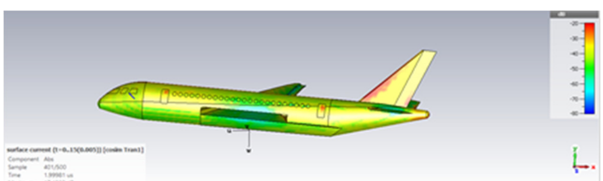

Figure 14: Surface current - Aircraft (CFC frame with aluminium mesh)

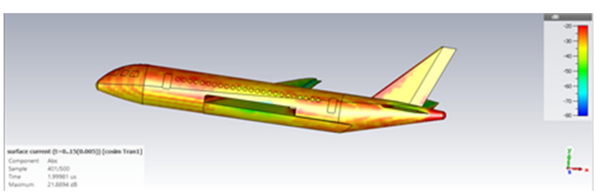

Figure 15: Surface current - Aircraft (CFC frame)

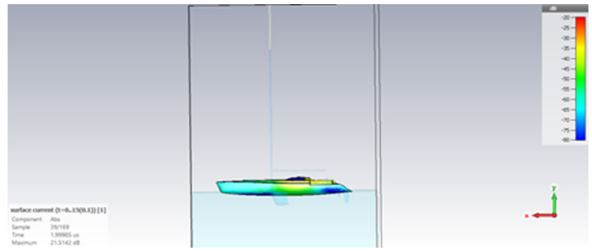

Figure 16: Surface current - Ship (Aluminium frame)

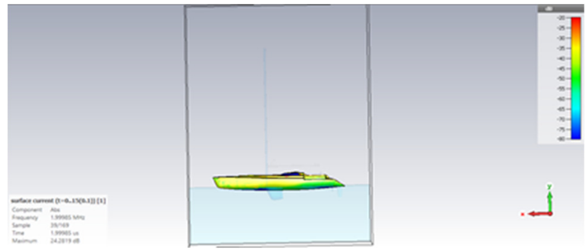

Figure 17: Surface current - Ship (Steel frame)

With lower frame conductivity, more current penetrates the vehicles and leads to higher internal surface current density. This is verified by the simulation results shown from Figure 11 to Figure 17. As the frame material changes from aluminium to CFC for aircraft and from aluminium to steel for the ship modeled the surface current increases.

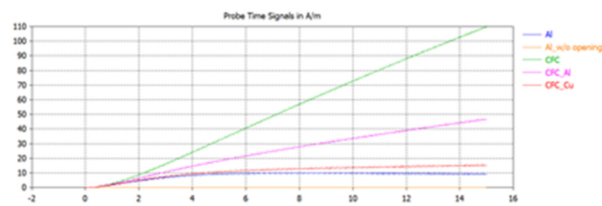

Figure 18: Magnetic field inside aircraft with different frame materials

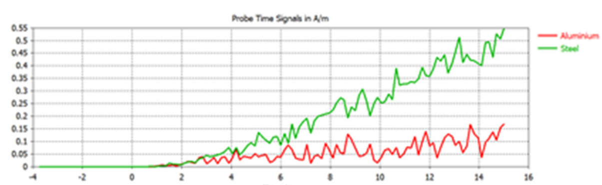

Figure 19: Magnetic field inside the ship with different frame materials

Similar to surface current, induced magnetic field inside of a vehicle when struck by lightning increases as the frame conductivity decreases. This is shown in the simulation results in Figure 18 and Figure 19.

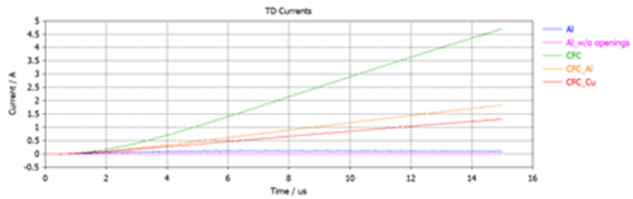

Figure 20: Induced current across a coaxial cable inside aircraft of different frame materials

Figure 20 shows the current induced in a coaxial cable when it is placed in aircraft made of different frame materials. The results are as expected and tally with the trend of internal surface current and magnetic field simulated when the same material is used. When the frame conductivity reduces, more current penetrates into the vehicle and a higher magnetic field is induced. This high magnetic field in turn induced more current in the coaxial cable.

VI. Distance from Frame/ Mast

Simulation results show that the induced magnetic field is higher at a location nearer to the vehicle's frame or mast. Figure 21-24 shows the streamlines of the magnetic field at the cross-section of the aircraft and ship modeled respectively.

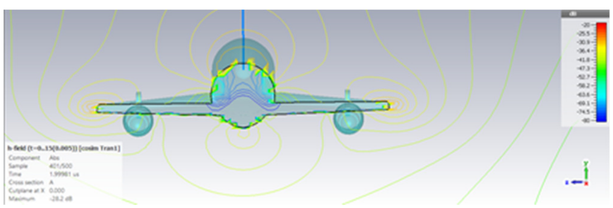
Figure 21: Induced magnetic field inside an aircraft

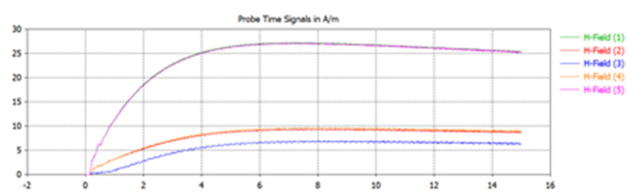

Figure 22: Magnetic field at a different distance from the frame

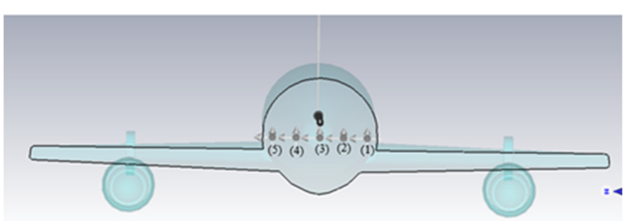

Figure 23: Location of the probes (aircraft)

Figure 24: Maximum magnetic field at a different distance from the frame

Figure 22 and Figure 26 show that the induced magnetic field for aircraft and ship at a different distance has the same pattern or waveform but as the distance becomes nearer, the curve shifted upwards. The location of the magnetic field probes for the aircraft and ship model are shown in Figure 23 and Figure 27 respectively. To compare the drop in the induced magnetic field with distance, the maximum field-induced is plotted against distance as shown in Figure 24 and Figure 28. It is showed that there is a sharper drop-in the magnetic field induced when it is near to the frame or mast and the drop becomes lesser as the distance increases.

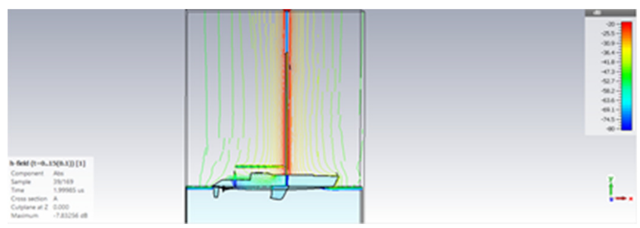
Figure 25: Induced magnetic field around the mast

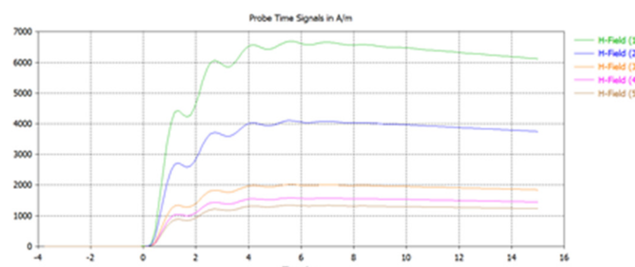

Figure 26: Magnetic field at a different distance from the mast

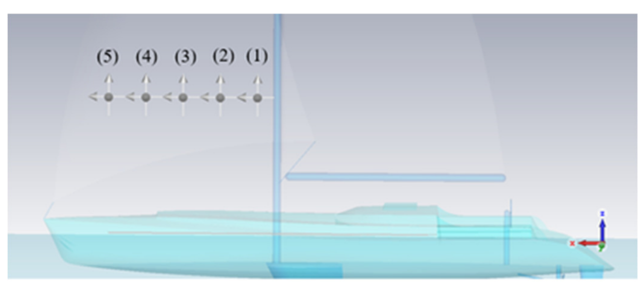

Figure 27: Location of the probes from mast

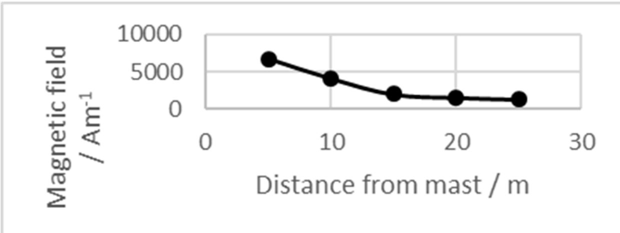

Figure 28: Maximum magnetic field at a different distance from the mast

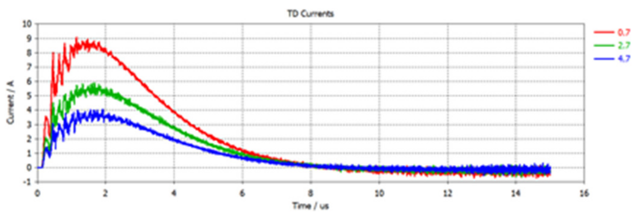

Figure 29: Induced current in a cable at a different distance from the frame

With a higher amount of magnetic field induced near to the frame, a cable placed nearer to the frame will have higher induced current. This is verified by results shown in Figure 29.

VII. Type of Cable

The effects on the type of cables used on the current induced inside the cable can be seen in Figure 30. It can be seen that coaxial cable with the shield grounded is most immune to induced current while the single wire is most ineffective. Grounding shield at only one end is effective to handle low frequency noise while grounding at both ends is more suitable for high frequency noise such as transients [14]. If the shield of the coaxial cable is ungrounded, the induced current will be similar to that of a single wire. Unshielded twisted pair (UTP) on the other hand offers better performance than normal dingle wire but is more susceptible as compared with a coaxial cable with the shield grounded.

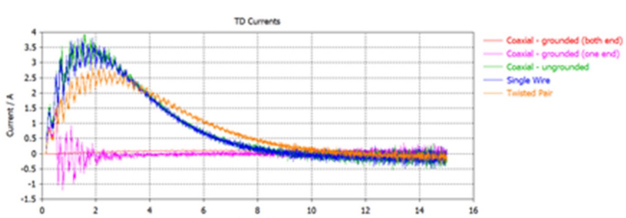

Figure 30: Induced current across different type of cables

VIII. Conclusion

As conclusion, a lightning strike is a dangerous event that can cause direct and indirect damage to equipment, structures and personnel. Indirect damage caused by lightning is through the induced magnetic field and power surge in cables that will disrupt the functionality of the equipment. Other than the lightning strike, electrostatic discharge and turning on/off of capacitive, inductor or motor load will also result in switching power surge. In order to protect the vehicle and personnel inside the vehicle, proper lightning and surge protection are required. To ensure that the vehicle and equipment used able to function properly in the event of a lightning strike or power surge, various standards and test waveforms are specified. A vehicle and equipment must be tested with specified waveforms and respective parameters before it can be put into service or sell to consumers. These test waveforms can be produced by using different circuits and components. For better protection, materials with high electrical conductivity should be used in the construction of the chassis or frame of the vehicle. Since the lightning current flows through the frame or mast in case of a ship, the induced magnetic field is stronger when it is nearer to the frame or mast. Therefore, by placing cables or circuits further from the frame or mast, the induced current in the cable can be reduced and less interruption will be faced by the equipment. Besides, to reduce current induced in a cable, shielded cable can be used especially for sensitive circuits. SPD shall be added to protect the system from power surge present or induced on the cables or circuits.

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