Protection Against Common Mode Currents on Cables Exposed to HIRF or NEMP

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***Abstract*—Above deck, cables on naval ships are exposed to high-intensity radiated fields and nuclear electromagnetic pulse (NEMP) that may cause conducted interference and generate electromagnetic fields that exceed the immunity levels of commercially available equipment above and below deck. Exposed cables, such as open power plugs or lighting cables, are modeled and characterized both as a monopole antenna perpendicular to the deck and as a transmission line, representing a cable close to the deck. The placement of an illuminated cable close to the deck is a good protection measure for long cables at low frequencies, which includes NEMP protection. The coupled pulse from a high-intensity NEMP illumination is not expected to cause damage on electric installations. It is shown that for exposed cable length of maximum 25 cm and not placed in the line of sight of transmitters above 400 MHz, no additional protection measures are needed.**

***Index Terms*—Electromagnetic compatibility, electromagnetic coupling, electromagnetic fields, marine electrical equipment.**

I. Introduction

Systems and cables on naval ships act as antennas and are susceptible to the external electromagnetic environment (EME), which may cause electromagnetic interference (EMI). Signals, radiated from above deck cables, may also be of concern for a possible increase of the noise floor of on-board receivers, as well as leaking information or detection by third parties. To prevent these problems, it is a best practice to avoid the installation of cables in the exposed upper-deck environment of naval ships, but that is not always practical and sometimes inevitable. Cables are necessary to feed auxiliary equipment, such as lighting, switches, auxiliary craft, general purpose power outlets, replenishment at sea (RAS) installations, etc. Cables can be protected by placing them in metallic trays or conduits [1] with proper bonding at all ends. Also this is not always practical. Lights are often nonconducting and long cables feeding auxiliary vessels are not always properly screened. To allow these situations, there is a need for a risk analysis of exposed cables as well as general quantified guidelines on how to install and protect them. A similar problem setup with a chain of wires acting as unwanted antennas, exposed cable shields, and unexposed cables is examined in [2]. In that paper, fields on the entire structure of an airplane are computed. This paper discusses design rules for the layout of unprotected cables above deck, assuming a well-protected environment below the deck of a ship. Unprotected cables are unscreened cables that are not properly protected by cable trays or metal pipes and therefore exposed to external fields.

The external EME on naval ships can be defined by four categories of electromagnetic threats. Protection against lightning [3], [4] and intentional electromagnetic interference [5] are out of the scope of this research. Two other categories of environments will be defined in Section II. One is the high-intensity radiated fields (HIRF) from powerful communication and radar transmitters, either on the own ship, or a nearby ship, sailing in convoy. The other environment is a nuclear electromagnetic pulse (NEMP) also known as high altitude electromagnetic pulse (HEMP). Conventionally, NEMP immunity is assessed by an NEMP simulator as in [6] that fires a full or reduced threat pulse and illuminates a system or a platform. Effects on the equipment under test are measured as voltages or currents on power or signal ports. This way of testing is time consuming and expensive. Therefore, a valid risk assessment based on calculations is beneficial in the development of quantitative design rules for electromagnetic compatibility.

The exposed cable will be characterized and modeled as a monopole antenna in Section III-A, and a lossless transmission line (TL) over a perfect ground in Section III-B. The results will be used in Section IV for a risk analysis to the environment in Section II. A recommendation for the layout of exposed cables will be given in the conclusion.

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II. Environment

Two types of environments will be defined in this section: The frequency domain HIRF environment in Section II-A and the time-domain NEMP in Section II-B.

A. HIRF Above Deck (Skyline)

The exposed environment on naval ships varies from a baseline of 200 V/m as described in several military test standards to several kV/m for powerful radar transmitters and is called the "skyline" [7] as in Fig. 1. This skyline is based on the calculated field at a 50 m distance in the boresight from a set of transmitters

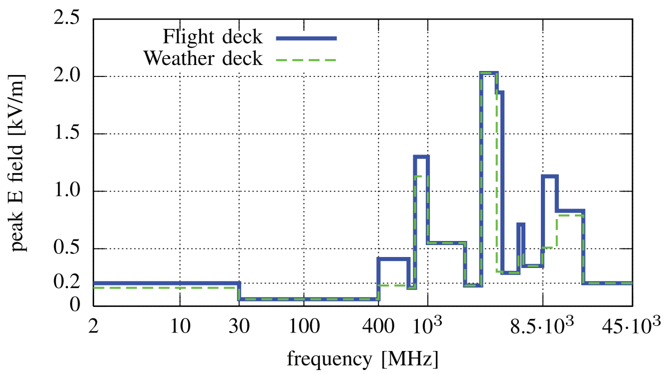

Fig. 1. Maximum expected exposed environment on a naval ship, AECTP 250, Table 258-1A [7], to be tailored for each ship.

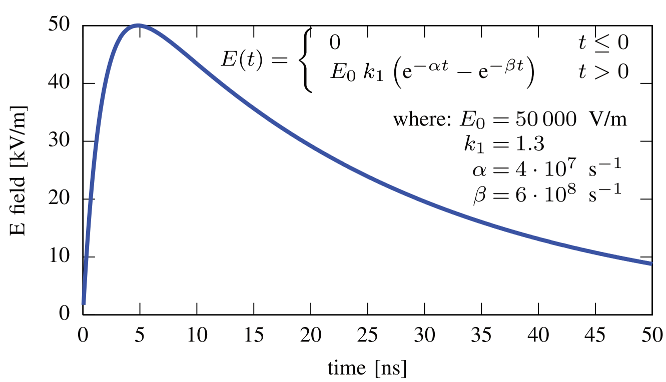

Fig. 2. Unclassified free-field NEMP environment [7, Fig. 256-6].

and must be tailored to each platform or fleet. The actual field strength will be lower on many places of the ship.

B. Nuclear Electromagnetic Pulse

Another threat for naval ships that will be analyzed is the early-time HEMP waveform or NEMP, defined in Leaflet 256 of AECTP 250 [7]. This waveform is identical to the IEC standard [8] and plotted in Fig. 2. The energy density of this pulse is 0.11 J/m^2, the rise-time is 2.5 ns, the fall-time or decay-time is 55 ns, the pulse width or full-width-half-maximum is 23 ns.

III. Modeling of Exposed Cables

The exposed cable will be characterized and modeled as a monopole antenna in Section III-A, and a lossless TL over a perfect ground in Section III-B.

A. Exposed Cable as a Vertical Monopole

The exposed cable acts as an unwanted wire antenna that puts a common mode (CM) signal on that cable with its antenna feedpoints at the point where it enters the metal hull of the ship. Examples are power outlets for general purpose or to feed auxiliary craft [see Fig. 3(a)], or complete installations, such as for RAS [see Fig. 3(b)], etc. These examples have in common that there is an unprotected exposed part above deck, without an

Fig. 3. Power outlet and installation for RAS.

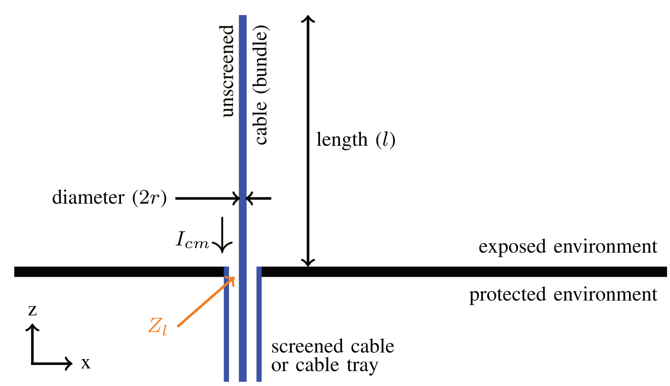

Fig. 4. Exposed cable modeled as a vertical monopole above a ground plane.

outer screen that can be properly bonded at hull penetration. Not all auxiliary equipment is made of metal with screened cables and steel cables may run through openings to the winches below deck. These examples are considered as a worst-case situation where the cable, perpendicular to the hull, is illuminated with an incident plane wave that matches this orientation as in Fig. 4. It is assumed that the generated CM signals propagate inside the ship in a cable tray or screened cable and may be reradiating.

Any thin wire-antenna is characterized by the Thévenin equivalent voltage, or electromotive force (EMF) V_i and internal complex impedance Z_i as in Fig. 5, for which the CM current I_{cm} through a load Z_l can be calculated. The tool numerical electromagnetics code [9], based on the method of moments (MoM) to solve an electric field integral equation model of thin wires, is used for the characterization of this equivalent circuit. Voltage V_i and impedance Z_i are calculated for a monopole of length l and radius $r = 0.005$ m that is illuminated by an incident plane wave with amplitude $E_i = 1$ V/m. The current I_{cm} has been calculated for different values of connected loads, based on these V_i and Z_i [10]. These current values match with the

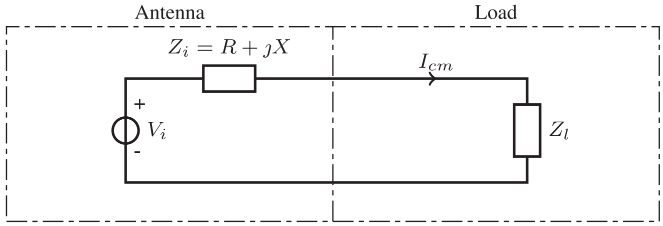

Fig. 5. Equivalent circuit of the illuminated monopole antenna.

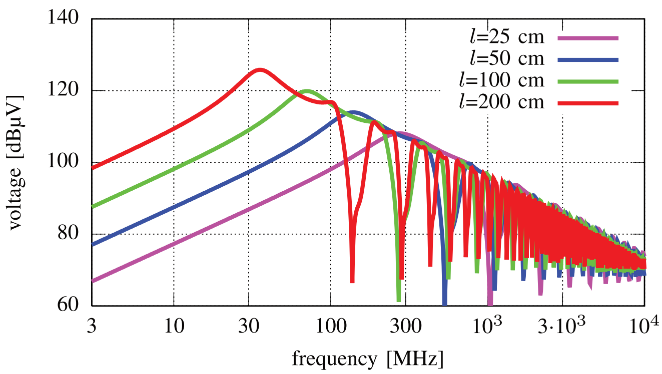

Fig. 6. Induced voltage in Z_l for different lengths (monopole) ($r = 0.005$ m, $Z_l = 100\ \Omega$, normalized to $E_i = 1$ V/m).

Fig. 7. Lighting in an exposed environment.

rule of thumb that an incident field of 1 V/m results in a CM current of 5–10 mA.

Fig. 6 shows the voltage over the load $Z_l = 100\ \Omega$, which is the representative for the characteristic impedance of a power cable, neglecting mismatches in the distribution network, for different lengths of the exposed part of the cable. This plot shows two interesting phenomena. For lower frequencies, the induced voltage goes up with length until the maximum just under the resonance frequency, i.e., a quarter wavelength. Above this frequency, the length of the exposed cable has no influence on the induced voltage any more.

B. TL Over a Perfect Ground Plane

It is a best practice to route cables close to a metal ground plane wherever possible to avoid coupling of electromagnetic fields into the cable. There is a need for a more quantitative design rule, knowing the amount of coupled energy. The light in Fig. 7 is an example of an exposed conductor close to a ground plane. The response of an illuminated cable, that is placed close to a perfect ground plane as in Fig. 8 is calculated. The cable is modeled as a lossless TL above a perfect ground plane. The cable is characterized by the length l, radius r, height h

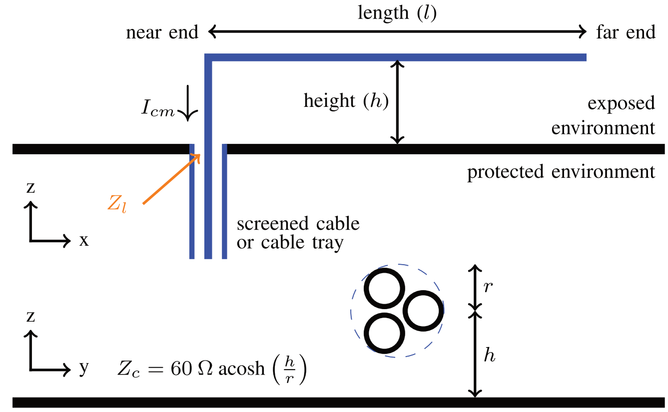

Fig. 8. Exposed cable configured as a TL above a ground plane with cross section.

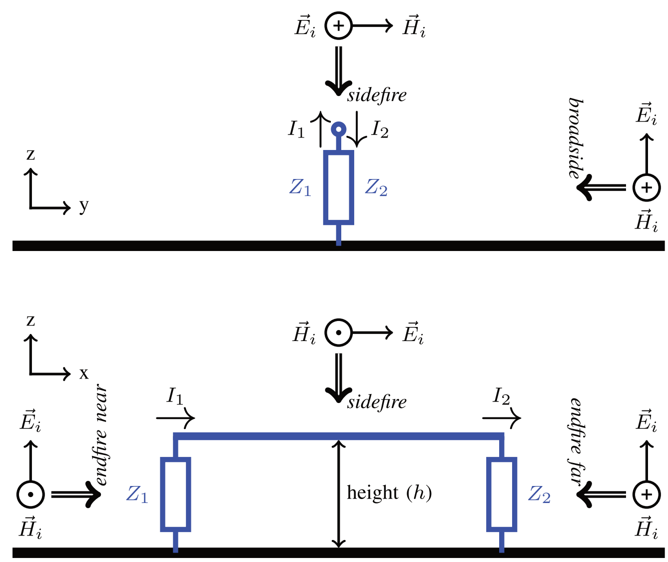

Fig. 9. Definitions of a TL above a ground plane with terminations at both sides and four incident directions and polarizations.

above a perfect ground and the terminations Z_1 and Z_2 (defined in Fig. 9) at the near and far end, respectively. The per-unit-length parameters are dependent on h and r, which result in a characteristic impedance $Z_c = 60\ \Omega\ \mathrm{acosh}\,(h/r)$, if losses are negligibly small and neglecting the proximity effect. This TL model is only valid for heights h that are much smaller than the wavelength. As a rule of thumb, a cutoff frequency where $\lambda = 4h$ is chosen in the results. Since the cables are placed in the proximity of the ground plane, currents will not be uniformly distributed but flow close to the ground plane, resulting in a slightly better protection by this ground plane compared to the TL model used. The TL is terminated at both sides with loads Z_1 and Z_2 and can be illuminated from different sides and polarizations. Fig. 9 shows the four independent, non-zero, illuminations. The currents I_1 and I_2 at the loads Z_1 and Z_2 are based on the well-known equations from Section 11.2.4 in [11]. The TL is terminated at the far end with Z_2, that is modeled as very high (1 MΩ) because the cable is not connected, and

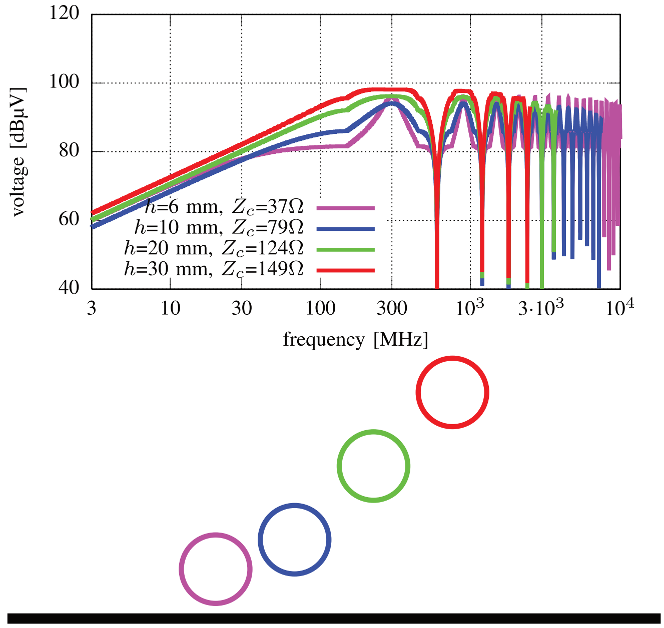

Fig. 10. Induced voltage in Z_l for different heights ($l = 0.5$ m, $r = 0.005$ m, $Z_1 = 100\ \Omega$, $Z_2 = 1$ MΩ, $E_i = 1$ V/m, truncated at $\lambda = 4h$).

terminated with $Z_1 = Z_l = 100\ \Omega$ at the near end, representing protected power cables inside the ship. For an open TL at the far end, the termination Z_2 can be chosen high, e.g., 1 MΩ. Alternatively, for $Z_2 \to \infty$, these equations reduce to:

$$\lim_{Z_2\to\infty} I_{1,\text{endfire far}} = 2hE_i \frac{\jmath \sin(\beta l)}{Z_c \cos(\beta l) + \jmath Z_1 \sin(\beta l)} \tag{1}$$

$$\lim_{Z_2\to\infty} I_{1,\text{endfire near}} = hE_i \frac{1-\cos(2\beta l) + \jmath \sin(2\beta l)}{Z_c \cos(\beta l) + \jmath Z_1 \sin(\beta l)} \tag{2}$$

$$\lim_{Z_2\to\infty} I_{1,\text{sidefire}} = 2hE_i \frac{\cos(\beta l) - 1}{Z_c \cos(\beta l) + \jmath Z_1 \sin(\beta l)} \tag{3}$$

$$\lim_{Z_2\to\infty} I_{1,\text{broadside}} = 2hE_i \frac{\jmath \sin(\beta l)}{Z_c \cos(\beta l) + \jmath Z_1 \sin(\beta l)}. \tag{4}$$

Calculations are done for different incident angles. The next figures show the envelope of the results of all four incident angles of the induced voltage in the exposed cable for variations in the height h (see Fig. 10), radius r (see Fig. 11), and length l (see Fig. 15). The incident field is normalized to an intensity of $E_i = 1$ V/m. The cross sections are to scale.

Fig. 12 shows the induced voltage in the exposed cable above the ground plane for variations in the length l. Comparing these results with the monopole configuration in Fig. 6, it can be concluded that placing a cable close to a ground plane reduces the induced voltage for long lines at the lower frequencies, but the decrease at the higher frequencies for the monopole is absent. Therefore, the best practice of just placing a cable against the deck must be followed very carefully. It is better to put it in a cable tray or place it under an overhanging deck or in the corner of a beam where it is not directly illuminated by an HIRF. Cables can be protected by a conductive structure (ground plane) if the geometry and layout are chosen carefully [1], [12], resulting in a low transfer impedance between the induced CM current through the structure and an induced voltage in the cable [13].

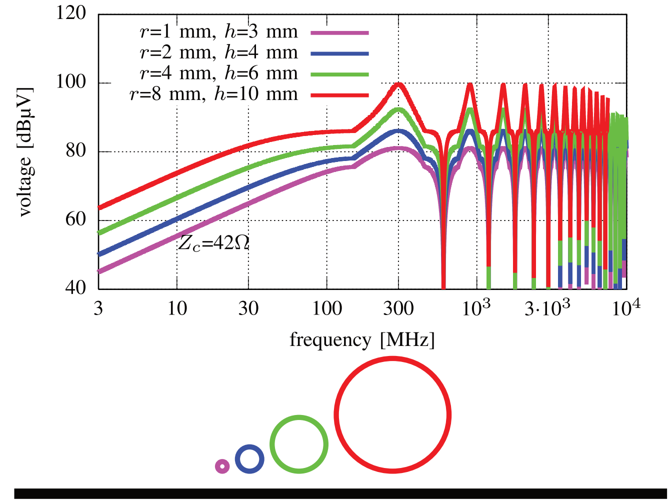

Fig. 11. Induced voltage in Z_l for different radii close to the ground plane ($l = 0.5$ m, $Z_1 = 100\ \Omega$, $Z_2 = 1$ MΩ, $E_i = 1$ V/m, truncated at $\lambda = 4h$).

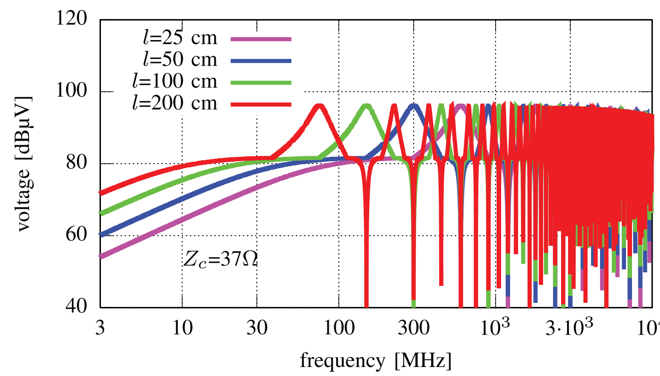

Fig. 12. Induced voltage in Z_l for different lengths (TL) ($r = 0.005$ m, $h = 0.006$ m, $Z_1 = 100\ \Omega$, $Z_2 \to \infty$, normalized to $E_i = 1$ V/m).

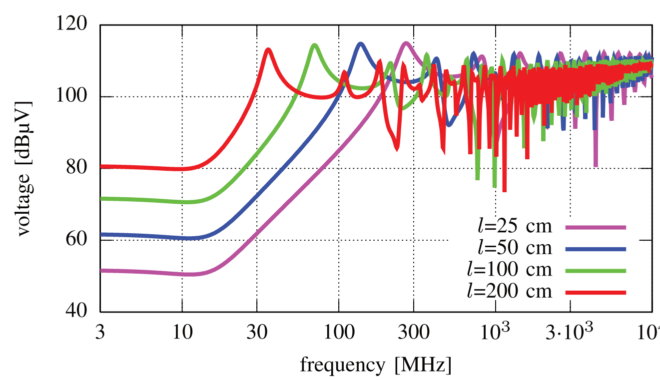

Fig. 13. Radiated field at 3 m distance for different lengths ($r = 0.005$ m, $V = 1$ V).

IV. Maximum Allowable Exposed Length

The results from the models of exposed cables are the response of the monopole model in Section III-A and TL model

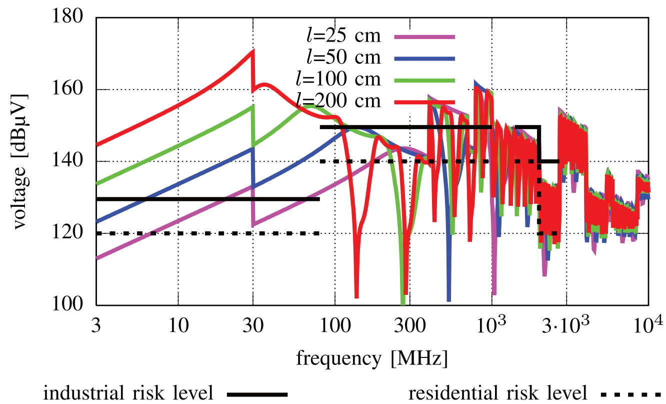

Fig. 14. Induced voltage in Z_l for a monopole of different lengths l and scaled to the skyline.

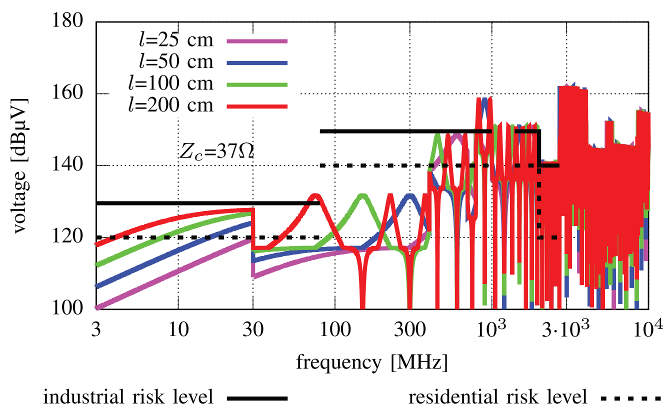

Fig. 15. Induced voltage in a TL for different lengths l and scaled to the skyline.

in Section III-B in frequency domain for an incident field that is normalized to 1 V/m. To do an interference-based risk analysis, these responses will be adapted to the HIRF values in Section IV-A and NEMP field strengths in Section IV-B environments. A possible filter is analyzed in Section IV-C. The risk from radiated emissions will be addressed in Section IV-D.

A. *Exposure to HIRF*

Electrical installations are in general more immune against HIRF disturbances than electronic circuits. But to get a quantitative rule, the immunity levels of the generic limits will be taken as the basis for a risk analysis in a worst-case situation. If only electrical installations are connected to the grid to which the exposed cable belongs rather than electronics, the field levels that couple with this cable can be somewhat higher. The limits for conducted immunity below 80 MHz are 3 V for residential and light-industrial equipment [14] and 10 V for industrial equipment [15]. The corresponding limits for radiated immunity above 80 MHz are 1–3 V/m [16] and 3–10 V/m [17].

The conducted immunity voltages are defined as an EMF with an internal impedance of 150 Ω including a coupling decoupling Network (CDN) and a 150 Ω termination in another CDN, according to the setup in [18, Fig. 1]. To generate the same CM current as in this setup, the allowed voltage at a cable of 100 Ω is the limit divided by 3, i.e., 1 and 3.3 V. This provides the worst-case situation that all disturbing current is absorbed by one piece of equipment on that cable.

A disturbing CM current that is picked up by an exposed cable could be reradiated below deck by an unprotected cable, i.e., without an additional screen or cable tray. To prevent reradiated electromagnetic field strengths above the generic limits, the coupled energy on the exposed cable has to be limited. The MoM calculation results in Fig. 13, where monopoles of different lengths are excited by a voltage source of 1 V, give a rule of thumb that 1 V produces about 0.3 V/m at a 3 m distance. This will be used to set the residential and industrial risk levels in the next results. The calculated fields for the lower frequencies and the peaks for the higher frequencies are constant for a constant voltage source. This behavior would be different for a constant current or constant power source.

Figs. 14 and 15 show the induced voltages that are picked up by the exposed cable. These voltages are obtained by multiplying the results in Figs. 6 and 12 by the so-called "skyline" for the flightdeck [7] from Fig. 1. Compared to the risk levels as defined above, it can be concluded that exposed and unprotected cables are a potential risk for conducted interference as well as reradiation below deck. This is a worst-case situation and requires a cautious interpretation for several reasons.

1) Much connected equipment will have a higher immunity limit than assumed here.
2) As mentioned in Section II-A, this skyline is based on a calculated field on a 50 m distance in the boresight from a set of transmitters and must be tailored to each platform or fleet.
3) The actual field strength will be lower than the worst case on many places of the ship. For example, there are radiation hazards (RadHaz) safe zones for personnel on naval ships, where the expected maximum field strengths are lower than the skyline mentioned before. In these zones, the risk from unprotected exposed cables is also lower.
4) The placement of an illuminated cable close to the deck is a good protection measure for long cables at low frequencies. For higher frequencies, such as ultra high-frequency (UHF) communication and radar, coupling can be further reduced by using a cable tray or even a metal pipe [1], [12] with proper bonding at all ends.
5) It is a best practice to assume that if a cable is not directly illuminated by a transmitter above roughly 400 MHz, the exposure can be neglected.

B. *Exposure to NEMP*

The results for the monopole and TL models in Section III give the coupled energy in a load for a plane wave illumination normalized to 1 V/m as a function of frequency. These results are the complex transfer functions from the incident field to the induced voltage. The discrete Fourier transform (DFT) of the time-domain NEMP waveform in Section II-B is multiplied with these complex transfer arrays. The inverse DFT of the obtained complex arrays give the real-valued time-domain

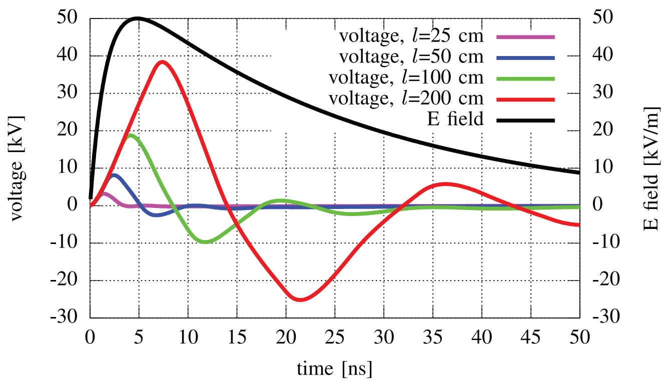

Fig. 16. Time-domain response of NEMP by a monopole with different lengths ($Z_l = 100\ \Omega$, $r = 0.005$ m).

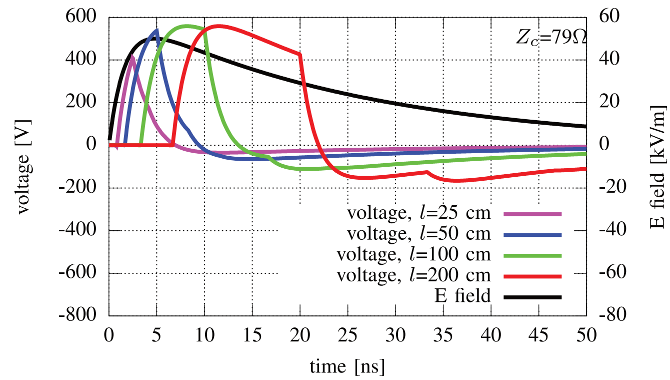

Fig. 18. Response of NEMP by a TL with different lengths ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m), endfire near.

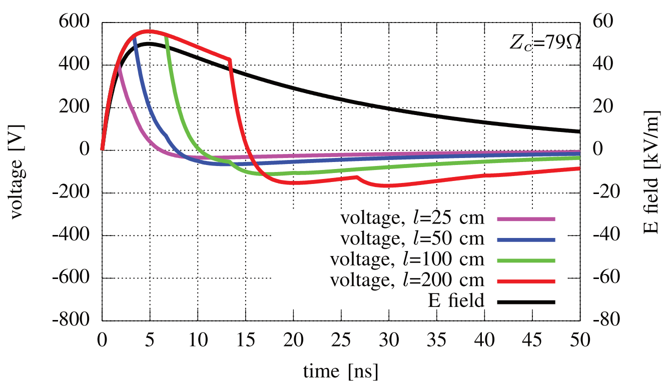

Fig. 17. Response of NEMP by a TL with different lengths ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m), endfire far and broadside.

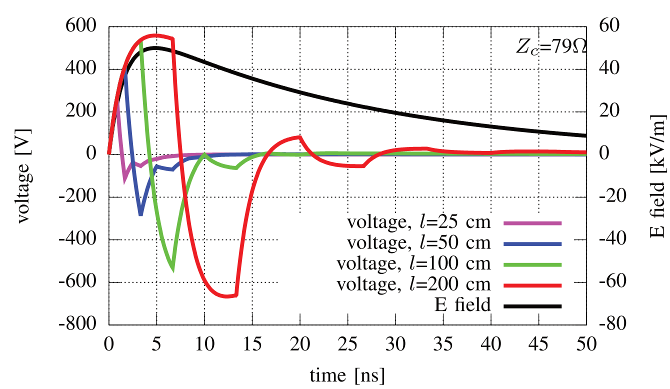

Fig. 19. Response of NEMP by a TL with different lengths ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m), sidefire.

waveforms that are present on the exposed cables. These are the currents I_{CM} at the feedpoints of both models in Figs. 4 and 8. The imaginary parts of the resulting time-domain waveforms vanish, because the discrete frequency domain results consist of an even real part and an odd imaginary part as a result from a real-valued time-domain waveform and a causal system. An alternative method is an analytical calculation as in [19].

1) Monopole Model: Fig. 16 shows the time-domain results for the monopole model for different lengths. It is observed that the pulse rises with approximately 6 kV/ns, regardless the length of the antenna. The amount of energy absorbed increases with the third power of the length increase, i.e., 10 dB increase for each doubling of the length.

2) Transmission Line Model: Figs. 17–19 show the result for a TL of varying length that is illuminated from endfire far, endfire near, and sidefire, respectively. Broadside illumination, (4), has the same results as endfire far, (1). The maximum induced voltage and energy are 1.12 kV and 0.34 mJ for the sidefire illumination and is reached from about 10 m length. For the other three illuminations, the maximum induced voltage and energy saturate at 0.56 kV and 0.10 mJ. Compared to [20], which is a study to the coupling into long lines that are much higher above the ground plane, the impact of NEMP is much lower in the case of cables that run very close to the ground plane. In our case, the ground plane helps in the protection against NEMP,

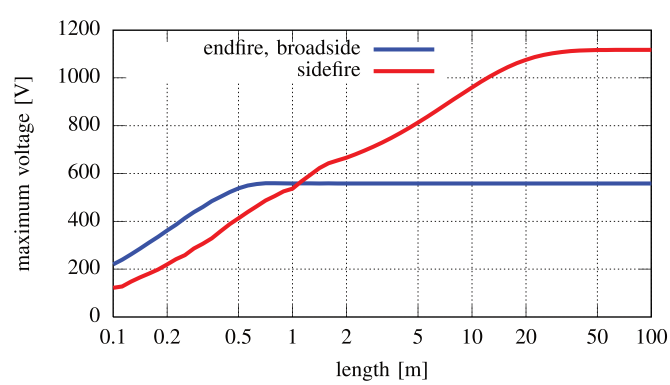

Fig. 20. Voltage amplitude at a TL due to NEMP as the function of the length ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m).

which appears to be a lower frequency problem compared to UHF communication and radar, where the protection does not work sufficiently.

Figs. 20 and 21 show the maximum voltage and the absorbed energy as function of the length. These two quantities do not increase above a certain length of the TL. This length is called the effective coupling length (ECL), which appears to be different for maximum voltage and absorbed energy. These results show that sidefire illumination is the worst case.

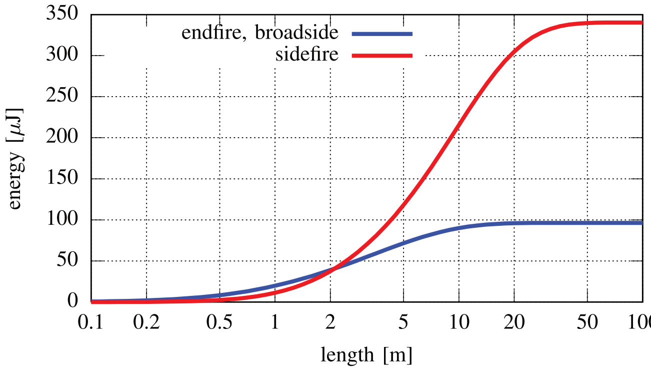

Fig. 21. Absorbed energy by a TL due to NEMP as the function of the length ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m).

3) Results: The calculations in this section show that the susceptibility of exposed cables is limited by the relatively low-frequency content of NEMP waveform and the high-frequency behaviour of the exposed cable, both in the monopole and in the TL model. The results from the calculations on both models show waveforms and amplitudes that are comparable to electrostatic discharge (ESD) [21] and electric fast transients (EFT) [22]. Since ESD requirements are defined at the enclosure port and EFT requirements at signal and power ports, the known immunity of equipment to the latter will be used in this analysis.

For the monopole model, the susceptibility increases with 10 dB for each doubling of the length. Up to 1 m length, the coupled waveform is comparable to EFT. Below 25 cm, also the amplitude is comparable to EFT. It is expected that equipment that can withstand EFT can also withstand NEMP if this monopole is shorter than 25 cm. For longer lengths, the susceptibility should be verified. Nowadays, most generic commercial of-the-shelf (COTS) equipment have varistors at their power port, but their Joules rating might be too low.

For the TL model, the susceptibility increases with length as well, but this susceptibility saturates at the ECL. For lengths below 50 cm, the waveform is comparable to EFT, but the amplitude is much lower. Longer lines are protected by surge protection devices, that are present as varistors in most generic COTS equipment, provided that the cables are mounted closely at the protecting ground plane.

C. Filtering

The effect of an additional filter to avoid electromagnetic signals to propagate into the hull of the ship is analyzed. This filter is placed at the point where the cable penetrates the hull as in Fig. 22. This filter is applied to each wire in the cable, i.e., one capacitor for each wire and either a common mode choke or one ferrite on the cable. The resulting current

$$I_{\text{cm}} = \frac{1}{Z_l + \jmath\omega L + Z_i\left(1 + \jmath\omega C\left(Z_l + \jmath\omega L\right)\right)} V_i \qquad (5)$$

that flows into the load Z_l is plotted in Fig. 23 after conversion to voltage. The internal impedance Z_i of the antenna is included

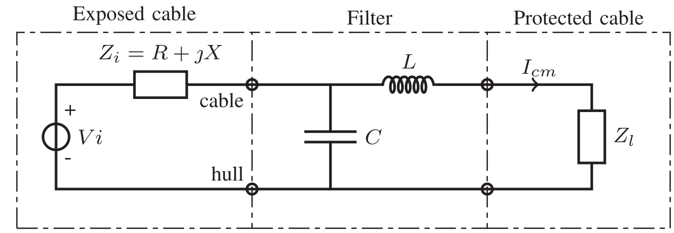

Fig. 22. Equivalent circuit of an illuminated exposed cable with filter.

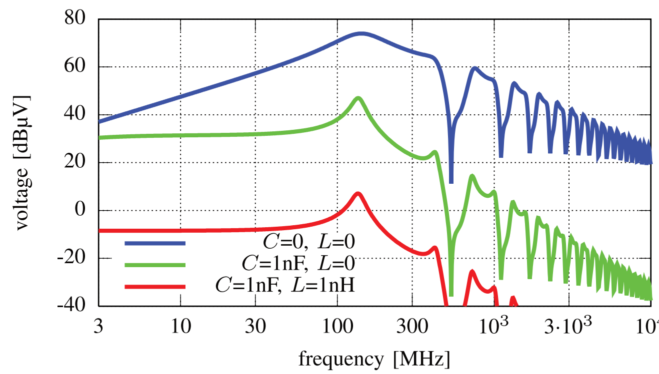

Fig. 23. Induced voltage for different C and L ($l = 0.5$ m, $r = 0.005$ m, $E_i = 1$ V/m, $Z_l = 100\ \Omega$).

in the characterization of the filter, which is important because it varies much as the function of frequency. Analysis on different configurations of the filter, not included here, show that the positions of C and L in this filter are important, i.e., the capacitor must be on the exposed side and the CM inductance on the protected side of the filter. The green line in Fig. 23 already shows an improvement by using just a capacitance C of 1 nF without the inductance L. Further improvement is achieved by adding a small inductance L. The chosen values of C and L are small, but sufficient in a worst-case scenario. The capacitance to earth of 1 nF will cause a negligible leakage current at 60 Hz on a naval IT-grid. An inductance of 1 nH can easily be achieved by a standard ferrite around the cable. Possible parasitic capacitance between windings of the inductance, in fact due to saturation of the coil [23], will be compensated by the capacitor as well.

D. Radiated Emissions

CM-conducted signals from below deck are radiated by cables in the exposed environment in the same way as exposed cables pick up field. These two mechanisms are reciprocal. The rationale behind immunity and emission limits are very different and so are the levels of the limits. Although it is difficult to compare military with civil standards [24], COTS equipment intended for use in a residential and light-industrial environment will produce a level of radiated emissions that will not have a great impact on the noise level of receivers used in a naval environment. Radio frequency protection is covered well in the commercial standard and it is assumed that there is sufficient distance and hull attenuation between this kind of equipment and the receive antennas above deck.

V. Conclusion

It is shown that HIRF from the above deck naval environment or an NEMP may cause conducted interference and generate electromagnetic fields below deck via unprotected cables that are inevitible above deck. Unprotected cables in an exposed environment are modeled and characterized both as a monopole antenna perpendicular to the deck and as a TL, representing a cable close to the deck. The length of the cable has no effect on the induced voltage if this length is more than a quarter wavelength for the monopole configuration and a half wavelength for the TL configuration. Long monopole configurations are a threat for low frequencies, such as HF (2–30 MHz) and NEMP. The placement of an illuminated cable close to the deck is a good protection measure for long cables at low frequencies, which includes NEMP protection. This measure does not show much improvement for the higher frequencies, such as UHF communication and radar, in which case it is better to hide these cables for this illumination.

A risk analysis shows that the induced voltages may exceed the generic limits for COTS equipment in a worst-case situation. If only electrical installations are connected to the grid to which the exposed cable belongs rather than electronics, the field levels that couple with this cable can be somewhat higher. Electrical installations are in general more immune against HIRF disturbances and NEMP than electronics. It appears that NEMP poses a low risk if exposed cables are kept short or placed against a protective ground plane. The coupled pulse from a high-intensity NEMP illumination is comparable to ESD or EFT and are not expected to cause damage on electric installations. It is recommended to limit the length of an exposed cable to 25 cm and to place exposed cables not in the line of sight (LoS) of transmitters above 400 MHz. For extreme cases, a simple CM filter can be effective if it is placed at the point where each cable penetrates the hull.

Design rule

On the above deck of a naval ship with the worst case expected HIRF,

1) limit the length of an exposed cable to 25 cm, and
2) do not place exposed cables in the LoS of transmitters above 400 MHz.
   a) If this rule cannot be met, a common mode filter can be applied at the entry point of the cable.
   b) If the exposed cable is in a RadHaz safe zone for personnel, and NEMP protection is not required, the length can be extended to 50 cm.

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