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Electromagnetic Field Study

The prediction of electromagnetic fields generated by wave energy converters.

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Record of Revisions

Revision	Date	Section and Paragraph	Description of Revision
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TABLE OF CONTENTS

TABLE OF FIGURES

1. EXECUTIVE SUMMARY

This report describes the characteristics of electromagnetic (EM) fields emitted from wave energy converters (WECs) in the marine environment. This study was commissioned with the goal of analyzing and synthesizing the expected EM field levels near energized wave energy converters in the coastal environment.

The basic physical theory was derived from the fundamental laws of electrical current and magnetism. Then, boundary conditions were applied to determine the local EM field effects. This report focuses on the EM field from WECs. A companion report discusses the EM fields generated by energized submarine power cables in the coastal marine environment.

This report presents a basic model for estimating the electromagnetic fields propagating from a point electromagnetic emission source. The model shows that the electric and magnetic fields in the sea decrease rapidly with distance from the source in the presence of a homogenous environment. The decay of the electric and magnetic fields depends on the nature of the source, and the physical parameters of the surrounding media, e.g. seawater and sediments.

2. INTRODUCTION

2.1 Purpose

This report estimates the localized EM field strengths created by energized wave energy converters. The purpose is to define the analytic methods for predicting the EM fields (EMF) produced by these devices. Therefore, the report focuses on identifying the range of values of EM signals created by wave energy converters in the near-shore marine environment.

2.2 Background

The Oregon Wave Energy Trust (OWET) was formed in 2007 to coordinate the development of power generation from offshore wave energy with the objective of generating 500 MW along the Oregon coast by 2025. The generated power will be transmitted to shore using subsea power cables to enable local or national distribution. The transmission of high power along such cables will induce both electric and magnetic fields into the sea. These EM fields may disturb marine species such as sharks and rays, which are sensitive to them. Together with the estimated or measured ambient EMF noise conditions, predictive results from this report can be used to estimate the environmental effects of placing such EM fields into the near shore environment.

2.3 Report Organization

This report contains several sections and supporting appendices. The first section contains the executive summary. The introduction (Section 2) describes the project's purpose, motivation, and background. Section 3 presents the methodology of analysis, followed by descriptions of the basic theories in Section 4. Section 5 presents the development of magnetic and electric field point source models. Section 6 provides overall conclusions. Appendix A contains a glossary of mathematical symbols, Appendix B provides an acronym list, and Appendix C contains reference materials.

3. METHODOLOGY

Two primary analytical models were developed to describe EM emissions from wave energy converters: (1) magnetic dipole, and (2) electric dipole. This approach is consistent with the controlled source magnetic and electric field models used in the geological community to analyze the upper structure of the earth's crust for oil exploration and scientific discovery.

While these models may not cover every possible type of wave energy converter, they do demonstrate the methodology to create analytical models that predict the range and magnitude of EMF values from an energized device. Further, they provide a basic toolset from which one can create variations to or adaptations of the initial model.

Readers are reminded that the modeled predictions for this work assume a simplified model, including the relatively homogeneity of the water and substrate conditions. Research into EMF generation and propagation, has demonstrated that a variety of factors, such as topographic, bathymetric, and geologic conditions, contribute to the natural generation and propagation of EM fields, particularly for the near shore environment. However, these conditions are not mathematically described herein. Thus, caution is urged when applying these predictive results to a specific environment.

4. BASIC THEORY

The basic theory for the development of an electromagnetic source, provided in a companion report, is replicated here for ease of reference.[1] Two fundamental relationships describe the magnetic and electric fields generated by an electrical conductor in a given medium. To simplify the analysis, the relative permeability (μ_r) and relative permittivity (ε_r) of the media are assumed constant. The magnetic field (B) as a function of distance (r) from the center of a conductor carrying a current I, can be derived from Ampere's Law:[2]

$$B(r) = \frac{I\mu_0\mu_r}{2\pi r} \qquad 1)$$

Where I = current in amps
μ_0 = permeability of free space ($4\pi \times 10^{-7}$ N/A^2)
μ_r = relative permeability of medium (~1 for non ferromagnetic materials)

Similarly, the electric field surrounding a line charge can be derived from Gauss's Law:[3,4]

$$E(r) = \frac{q}{2\pi r\varepsilon_0\varepsilon_r} \qquad 2)$$

Where q = charge/unit length (coulomb/m)
ε_0 = permittivity of free space (8.66×10^{-12} F/m)
ε_r = relative permittivity of material surrounding line charge (1 for air)

[1] Slater, M., Schultz, A. (2010). The prediction of electromagnetic fields generated by submarine power cables. Oregon Wave Energy Trust

[2] http://farside.ph.utexas.edu/teaching/316/lectures/node75.html

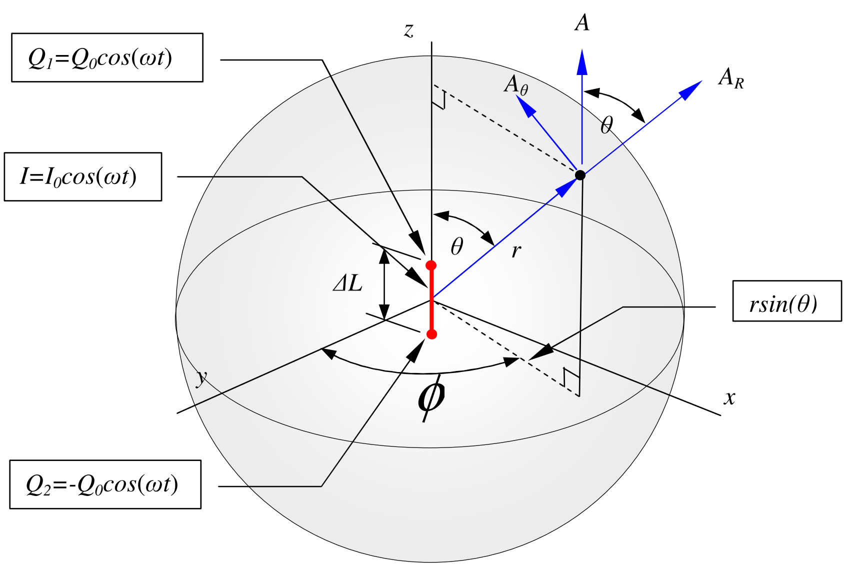
[3] http://en.wikipedia.org/wiki/Gauss's_law

[4] http://35.9.69.219/home/modules/pdf_modules/m133.pdf

5. EM FIELDS INDUCED IN THE SEA BY A POINT SOURCE

This discussion assumes that the power generation unit for each WEC will be housed within a surface or near-surface expression, or buoy, which will produce electromagnetic emissions that may propagate into the sea. The section develops and describes the application of basic theory to the problem of assessing the magnitude of the electric and magnetic fields induced in the sea from a point source of electromagnetic energy.

A convenient method for charactering the fields from a point source is to consider the generator as an electric dipole as shown in Figure 1.



Q_1, Q_2, and Q = charge	(Coulombs)
$\omega = 2\pi f$	(radians/s)
t = time	(s)
ΔL = length of dipole	(m)
I, I_0 = Current	(A)

Figure 1 – Hertzian or Electric Dipole Model

The derivation of the electric and magnetic fields produced from a Hertzian Dipole (Ida 2004) is summarized below.

The magnetic potential ($A(r)$) at point P is given by:

$$A(r) = \hat{z}\frac{\mu_0 \mu_r I_0 \Delta L}{4\pi r}\exp(-i\beta' r) \qquad 3)$$

Where β' = phase constant = $\dfrac{\omega}{v_p}$ (radians per meter)

And v_p = phase velocity (m/sec)

$\hat{z} =$ unit vector in z

In spherical coordinates, the components of the magnetic potential are:

$$A_R = A_Z \cos(\theta) = \frac{\mu_0 \mu_r I_0 \Delta L \cos(\theta)}{4\pi r}\exp(-i\beta' r)$$

$$A_\theta = A_Z \sin(\theta) = \frac{\mu_0 \mu_r I_0 \Delta L \sin(\theta)}{4\pi r}\exp(-i\beta' r)$$

Therefore, the magnetic vector potential is given by:

$$A(r,\theta) = \hat{r}\frac{\mu_0 \mu_r I_0 \Delta L \cos(\theta)}{4\pi r}\exp(-i\beta' r) - \hat{\theta}\frac{\mu_0 \mu_r I_0 \Delta L \sin(\theta)}{4\pi r}\exp(-i\beta' r) \qquad 4)$$

where $\hat{\theta} =$ unit vector in θ

$\hat{r} =$ unit vector in r

The magnetic field B can now be determined using:

$$B(r,\theta) = \nabla \times A(r,\theta) = \hat{\phi}\frac{\mu_0 \mu_r I_0 \Delta L \sin(\theta)}{4\pi}\left[\frac{i\beta'}{r} + \frac{1}{r^2}\right]\exp(-i\beta' r)$$

$$B(r,\theta) = \hat{\phi}\frac{\mu_0 \mu_r I_0 \beta'^2 \Delta L \sin(\theta)}{4\pi}\left[\frac{1}{\beta' r} + \frac{1}{(\beta' r)^2}\right]\exp(-i\beta' r) \qquad 5)$$

where $\hat{\phi} =$ unit vector in ϕ

The power frequency will be 60 Hz, which equates to a wavelength (λ) of 5000 km, which is much greater than the radii of interest (i.e. 0 to 1 km). Therefore, a near field approximation (i.e. $r < \lambda/1000$) for the maximum magnetic field, can be applied to equation 5), which gives:

$$B(r) = \frac{\mu_0 \mu_r I_0 \Delta L}{4\pi r^2} \tag{6)}$$

An expression for the electric field can be derived from equation 5) using Maxwell's (1873) equations, which gives:

$$\begin{aligned} E(r,\theta) = \frac{c^2}{i\omega} \nabla \times B(r,\theta) = -\hat{r} \frac{Z I_0 \Delta L \beta'^2 \exp(-i\beta' r)\cos(\theta)}{2\pi} \left[\frac{1}{(i\beta' r)^2} + \frac{1}{(i\beta' r)^3} \right] \\ - \hat{\theta} \frac{Z I_0 \Delta L \beta'^2 \exp(-i\beta' r)\sin(\theta)}{4\pi} \left[\frac{1}{i\beta' r} + \frac{1}{(i\beta' r)^2} + \frac{1}{(i\beta' r)^3} \right] \end{aligned}$$

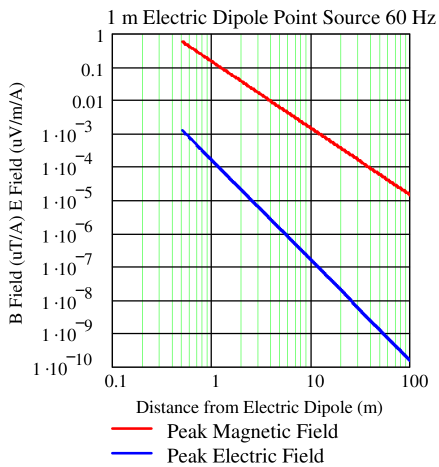
The maximum E field occurs when $\theta = 0$, and a near field approximation (i.e. $r < \lambda/1000$) can be adopted, which gives:

$$E(r) = -\frac{Z I_0 \Delta L}{2\pi \beta' (ir)^3} \tag{7)}$$

Where Z is the characteristic impedance of the sea:

$$Z = \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon_r}} = \sqrt{\frac{\mu_0 \times 1}{\varepsilon_0 \times 81}} = 41.86\Omega$$

A plot of the peak electric and magnetic fields as a function of distance from a dipole length of 1 m, presuming that no shielding surrounds the energy source, is shown in Figure 2.



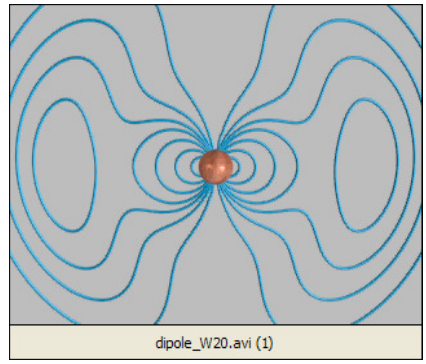


Figure 2 – Normalized Magnetic and Electric Fields vs. Distance from Electric Dipole
Dipole length = 1 m. Frequency = 60 Hz. Current I_0 = 1A

A magnetic dipole could also be considered as the emission source rather than an electric dipole. The fields for this case are (Ida, 2004):

$$E_\phi = \frac{Z\beta'^3 I_0.dA\sin(\theta)\exp(-i\beta' r)}{2\pi}\left[\frac{i}{\beta' r}+\frac{1}{(\beta' r)^2}\right]$$

$$B_r = \frac{i\beta'^3\mu_0\mu_r I_0 dA\cos(\theta)\exp(-i\beta' r)}{2\pi}\left[\frac{1}{(\beta' r)^2}-\frac{i}{(\beta' r)^3}\right]$$

$$B_\theta = \frac{i\beta'^3\mu_0\mu_r I_0 dA\sin(\theta)\exp(-i\beta' r)}{4\pi}\left[\frac{i}{\beta' r}+\frac{1}{(\beta' r)^2}-\frac{i}{(\beta' r)^3}\right]$$

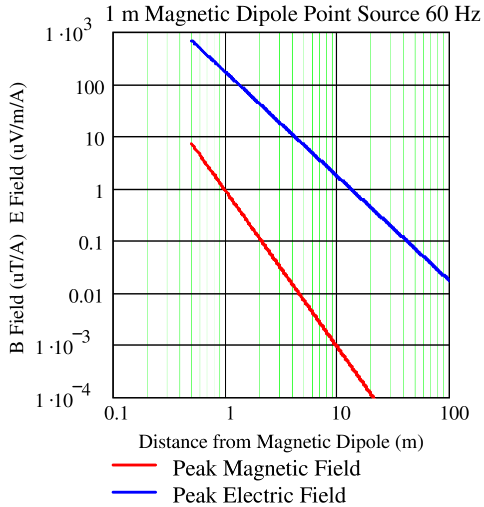
The corresponding near field approximations (i.e. $r < \lambda/1000$) for the maximum magnetic and electric fields are:

$$E(r) = \frac{ZI_0 dA\beta'}{4\pi r^2} \qquad 8)$$

$$B(r) = \frac{\mu_0\mu_r I_0 dA}{2\pi r^3} \qquad 9)$$

Where dA = loop area = πa^2 (m^2) and a = loop radius (m)

The peak fields for a 1 m radius current loop, again with no shielding around the source, are shown in Figure 3.



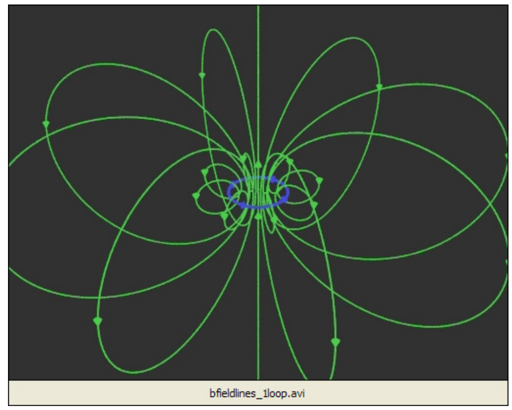


Figure 3 – Normalized Magnetic and Electric Fields vs. Distance from Magnetic Dipole Dipole diameter = 1 m. Frequency = 60 Hz. Current = 1A

6. CONCLUSIONS

This report presents models for predicting the electromagnetic fields produced by wave energy converters. The models are based on fundamental physical laws.

The basic model presented estimates the electromagnetic fields propagating from a point electromagnetic emission source. The model shows that the electric and magnetic fields in the sea decrease rapidly with distance from the source. The decay of the electric and magnetic fields depends on the nature of the source (i.e. electric or magnetic):

For a magnetic dipole source: $E \propto \frac{1}{R^2}$ and $B \propto \frac{1}{R^3}$

For an electric dipole source: $E \propto \frac{1}{R^3}$ and $B \propto \frac{1}{R^2}$

The normalized magneto-hydrodynamic electric field produced when seawater moves through the earth's magnetic field is approximately 0.515 V/m/knot/T. Changing magnetic fields in the presence of a conductor creates induced electric field effects, and furthermore, motion of a magnetic field within a conductor (e.g. seawater) for induced electric field effects, it is given that energized wave energy converters will most likely form induced electric field effects. Primary factors affecting the induced electric field near each WEC will be related to relative speed of motion between the device and surrounding seawater, as well as the strength of the magnetic field produced by the power generation unit on board the device.

APPENDIX A – GLOSSARY OF SYMBOLS

$\alpha, \beta, \theta, \phi$	Angle	radians
a	Current loop radius	m
A	Magnetic vector potential	$Wb{\cdot}m^{-1}$ or $T{\cdot}m$
B	Magnetic Field	Tesla
β'	Phase constant	$radian{\cdot}sec^{-1}$
C', C	Transmission line capacitance	$F{\cdot}m^{-1}$
dA	Area of current loop	m^2
δ	Skin depth	m
E	Electric field	$V{\cdot}m^{-1}$
ε_0	Permittivity of free space	8.66×10^{-12} $F{\cdot}m^{-1}$
ε_r	Relative permittivity	
f	Power frequency	Hz
G'	Transmission line conductance	$S{\cdot}m^{-1}$
h	Depth	m
I	Current	Amperes
l	Length	m
L'	Transmission line inductance	$H{\cdot}m^{-1}$
λ	wavelength	m
μ_0	Permeability of free space	$4\pi \times 10^{-7}$ $N{\cdot}Amp^{-2}$
μ_r	Relative permeability	
v_p	Phase velocity	$m{\cdot}sec^{-1}$
v	Sea water flow velocity	$m{\cdot}sec^{-1}$
Q	Charge	coulomb
q	Charge/unit length	$coulomb{\cdot}m^{-1}$
r	Radial distance	m
R'	Transmission line resistance	$\Omega{\cdot}m^{-1}$
R_1, R_2, R, R_C	Radii	m
ρ	Resistivity	$\Omega{\cdot}m$

σ	Conductivity	$S \cdot m^{-1}$
$\hat{\theta}$	Unit vector in θ	
V	Potential	volts
υ	Volume fraction	
ω	angular frequency	$radians \cdot sec^{-1}$
x, y, z	Cartesian coordinates	m
Z	Impedance	Ω
Z'	Transmission line impedance	Ω
$\hat{z}$	Unit vector in z	

APPENDIX B – ACRONYMS

ASW	anti-submarine warfare
B-field	magnetic field
BWEA	British Wind Energy Association
CA	California
CGS	centimeter-gram-second
CMACS	Centre for Marine and Coastal Studies
COWRIE	Collaborative Offshore Wind Research Into The Environment
DECC	Department for Energy and Climate Change
DoI	Department of Interior
EA	Environmental Assessment
E-field	electric field
EIS	Environmental Impact Statement
EM	electromagnetic
EMF	electromagnetic field
FEA	Finite Element Analysis
Hz	Hertz, cycles per second
MHD	magneto hydrodynamic
MHz	megahertz
MKS	meter-kilogram-second
MMS	Minerals Management Service
ODFW	Oregon Department of Fish and Wildlife
OPT	Ocean Power Technologies
OR	Oregon
OWET	Oregon Wave Energy Trust
PSD	Power spectral density
RMS	Root Mean Square
SI	International System of Units
SIO	Scripps Institute of Oceanography
THz	terahertz
UK	United Kingdom
WA	Washington
WEC	Wave Energy Converter

APPENDIX C – BIBLIOGRAPHY

Ida, Nathan. (2004). *Engineering Electromagnetics*, (2nd ed.). New York, NY: Springer, pp. 1124-1129.

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