Chapter 8
Electromagnetic Fields

Thoroughly conscious ignorance is the prelude to every real advance in science.

—James Clerk Maxwell

8.1 The Electromagnetic Field

The *electromagnetic field* can be seen as the combination of an electric field $\vec{E}$ [V/m] and a magnetic field $\vec{H}$ [A/m] traveling in the same direction. Figure 8.1 shows an electromagnetic field in form of a plane wave, where the electric field and the magnetic field are perpendicular to each other.

The *Poynting vector*[1] $\vec{S}$ [W/m^2] represents the direction of propagation of an electromagnetic wave and the complex power density vector of a radiated electromagnetic field in [W/m^2]. $\vec{S}$ is defined as the cross product of the two vector fields $\vec{E}$ and $\vec{H}^*$ [1]:

$$\vec{S} = \vec{E} \times \vec{H}^* \tag{8.1}$$

where,

$\vec{S}$ = the directional energy flux vector (the energy transfer per unit area per unit time) of an electromagnetic field in [W/m^2]
$\vec{E}$ = electric field vector in [V/m]
$\vec{H}^*$ = complex conjugate of the magnetic field vector $\vec{H}$ in [A/m]

Instead of working with complex field vectors, it is often much more practical to work with the average power density S_{avg} [W/m^2]. For a uniform plane wave

[1] The Poynting vector represents the directional energy flux (the energy transfer per unit area per unit time) of an electromagnetic field. The SI unit of the Poynting vector is the watt per square meter [W/m^2]. It is named after its discoverer John Henry Poynting who first derived it in 1884.

R. B. Keller, *Design for Electromagnetic Compatibility–In a Nutshell*,
https://doi.org/10.1007/978-3-031-14186-7_8

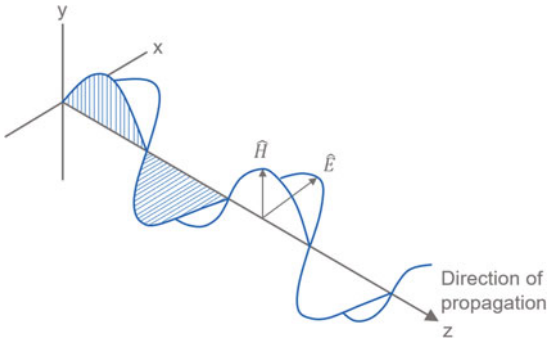

Fig. 8.1 An electromagnetic field (plane wave) can be seen as the combination of an electric field and a magnetic field (perpendicular to each other and traveling in the same direction)

(electromagnetic field in the far-field, where the wave impedance $\underline{Z}_w$ [Ω] is equal to the intrinsic impedance $\underline{\eta}$) in a lossless medium ($\underline{\epsilon}_r = 1.0$ and $\underline{\mu}_r = 1.0$), the calculation of the average power density S_{avg} [W/m^2] can be simplified to:

$$S_{avg} = \frac{1}{2}|\vec{E}| \cdot |\vec{H}| = \frac{|\vec{E}|^2}{2\eta} = \frac{|\vec{H}|^2\eta}{2} \tag{8.2}$$

where,

$|\vec{E}|$ = amplitude (magnitude) of the electric field vector/phasor in [V/m]
$|\vec{H}|$ = amplitude (magnitude) of the magnetic field vector/phasor in [A/m]
η = intrinsic impedance of the medium where the uniform plane wave is traveling though in [Ω]

In Eq. 8.2 the factor 1/2 can be omitted for RMS values of $\vec{E}$ [V/m] and $\vec{H}$ [A/m]. For free space, η [Ω] can be set to $\eta_0 = 377\,\Omega$. More details about the electromagnetic and other physical fields can be found in Appendix D.

8.2 Electromagnetic Field Characteristics

Three parameters determine the electromagnetic field characteristics [4]:

- **Source.** The physics of an antenna determines the wave impedance $\underline{Z}_w$ [Ω] and the distance of the near-field/far-field boundary from the antenna. An antenna can be an intentional antenna like a dipole, horn or loop antenna, or an unintended antenna like a cable or a PCB trace.
- **Media.** Every medium has its intrinsic impedance $\underline{\eta}$ [Ω]. The medium that surrounds the source (e.g., air, plastics, metal) and the medium through which the electromagnetic wave is traveling influence the wave impedance $\underline{Z}_w$ [Ω] and the attenuation.
- **Distance.** The distance between the source and the point of observation is an essential factor. Close (compared to the wavelength λ [m]) to the source, the field

properties are determined primarily by the source characteristics (low-impedance or high-impedance source). Far from the source, the field depends mainly on the medium through which the field is propagating. Therefore, the space around a radiation source (antenna) can be split into two regions: the near-field and the far-field.

More details about the near-field, the far-field, the wave impedance $\underline{Z}_w$ [Ω], and the intrinsic impedance $\underline{\eta}$ [Ω] are presented in the following Sects. 8.3–8.5.

8.3 Near-Field vs. Far-Field

As an EMC design engineer, there is no way around the near- and far-field topic. For example, for shielding, it is crucial whether the electromagnetic wave to be shielded is a near-field or a far-field wave (see Chap. 13). Moreover, for EMC emission troubleshooting, it is crucial to know if a measurement takes place in the near-field or the far-field because different probes and antennas have to be used accordingly:

- **Measurement in the near-field.** Special near-field probes are used (see Fig. 9.3 on page 112).
- **Measurement in the far-field.** Typically, E-field antennas are used (see Fig. 9.1 on page 112).

The electromagnetic field around an antenna can be divided into three regions [1]:

1. Reactive near-field (see Sect. 8.3.1.1)
2. Radiating near-field (see Sect. 8.3.1.2)
3. Far-field (see Sect. 8.3.2)

The regions depend on the maximum linear dimension of the antenna D [m] and the wavelength of the signal λ [m] (see Fig. 8.2):

- **Electrically small antennas: D** $< \lambda/(2\pi)$**.** The reactive near-field is significant. For electrically small antennas, the radiating near-field and the far-field are minimal, if they exist at all.
- **Electrically large antennas: D** $> \lambda/(2\pi)$**.** All three regions are significant: the reactive near-field, the radiating near-field, and the far-field.

8.3.1 Near-Field

In the *near-field*—also called *Fresnel zone*—the wave impedance $\underline{Z}_w$ [Ω] depends primarily on the source, and the electric and magnetic fields have to be considered separately (because the ratio of $|\underline{E}(z)|/|\underline{H}(z)|$ is not constant). Usually, there is

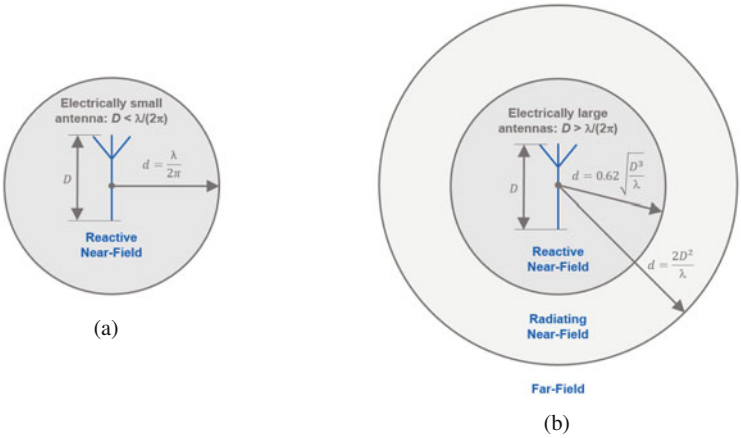

Fig. 8.2 Approximate near-field to far-field boundary [1]. (**a**) The reactive near-field of electrically small antennas. (**b**) The near-/ and far-field of electrically large antennas

either the electric E-field or the magnetic H-field predominant in the near-field [5]:

- **Predominant E-field:**
  - The source voltage is high compared to the source current (electric dipole).
  - The source impedance is high (e.g., electric dipole antennas).
  - The wave impedance near the antenna is high.
  - E-field attenuates with a rate of $1/d^3$ in the near-field ($d =$ distance to source).
  - H-field attenuates with a rate of $1/d^2$ in the near-field ($d =$ distance to source).
- **Predominant H-field:**
  - The source voltage is low compared to the source current.
  - The source impedance is low (e.g., loop antennas, magnetic dipole antennas).
  - The wave impedance near the antenna is low.
  - E-field attenuates with a rate of $1/d^2$ in the near-field ($d =$ distance to source).
  - H-field attenuates with a rate of $1/d^3$ in the near-field ($d =$ distance to source).

As mentioned above, the near-field can be divided into the following two regions: the reactive near-field and the radiating near-field.

8.3.1.1 Reactive Near-Field

In the *reactive near-field*, energy is stored in the electric and magnetic fields very close to the source but not radiated from them. Instead, energy is exchanged between the signal source and the fields.

In the case of $D < \lambda/(2\pi)$—this means that the antenna is not a very effective radiator—the reactive near-field extends until the distance d [m] from the antenna by Balanis [1]:

$$d_{reactive-near-field} \leq \frac{\lambda}{2\pi} \tag{8.3}$$

In the case of $D > \lambda/(2\pi)$—where there is the chance that the antenna is an effective radiator—the reactive near-field extends until the distance d [m] from the antenna by:

$$d_{reactive-near-field} \leq 0.62\sqrt{\frac{D^3}{\lambda}} \tag{8.4}$$

where,

λ = wavelength of the sinusoidal signal in [m]
D = maximum linear dimension of the antenna in [m]. $D = l$ for a wire antenna.

8.3.1.2 Radiating Near-Field

If a *radiating near-field* exists, then it is defined as the region between the reactive near-field and the far-field. In the radiative or radiating near-field, the angular field distribution depends on distance d from the antenna, unlike in the far-field where it does not depend on the distance. In addition, in the radiating near-field, the radiating power density is greater than the reactive power density.

If the antenna has a maximum dimension D [m] that is small compared to the wavelength λ [m], the radiating near-field region may not exist.

In the case of $D > \lambda/(2\pi)$, the radiating near-field begins after the reactive near-field region has ended ($d_{reactive-near-field}$) and ends where the far-field begins [1]:

$$d_{radiating-near-field} = 0.62\sqrt{\frac{D^3}{\lambda}} \ldots \frac{2D^2}{\lambda} \tag{8.5}$$

where,

λ = wavelength of the sinusoidal signal in [m].
D = maximum linear dimension of the antenna in [m]. $D = l$ for a wire antenna.

8.3.2 Far-Field

In the *far-field*—also called *Fraunhofer region*—the E- and H-fields move perpendicular (orthogonal) and in phase to each other and form a plane wave.

- E- and H-field attenuate with a rate of $1/d$ in the far-field (d = distance to source) and therefore the power density S_{avg} [W/m^2] of the electromagnetic wave attenuates with $1/d^2$.
- The wave impedance in free-space (air) is $\eta_0 = 377\,\Omega$.

There is usually only a far-field region in the case of $D > \lambda/(2\pi)$, where λ [m] is the wavelength of the signal and D [m] is the maximum linear dimension of the antenna. However, if there is a far-field, it starts roughly at the following distance d [m] from the antenna [1]:

$$d_{far-field} > \frac{2D^2}{\lambda} \tag{8.6}$$

where,

λ = wavelength of the sinusoidal signal in [m]
D = maximum linear dimension of the antenna in [m]. $D = l$ for a wire antenna.

8.4 Intrinsic Impedance η

8.4.1 Intrinsic Impedance of Any Media

The *intrinsic impedance* $\underline{\eta}$ [Ω] is a property of a medium, and it influences the electromagnetic waves that are traveling through that medium. The intrinsic impedance is dependent on the conductivity, permittivity and permeability of the medium. It is a complex number and defined as [6]:

$$\underline{\eta} = \sqrt{\frac{\underline{\mu}}{\underline{\epsilon}}} = \sqrt{\frac{\mu' - j\mu''}{\epsilon' - j\epsilon''}} = \sqrt{\frac{\mu'' + j\mu'}{\epsilon'' + j\epsilon'}} = \sqrt{\frac{\mu''\omega + j\omega\mu'}{\epsilon''\omega + j\omega\epsilon'}} \tag{8.7}$$

where,

$\underline{\mu} = \underline{\mu}_r\mu_0 = \mu' - j\mu''$ = complex permeability of the medium in [H/m]
$\underline{\epsilon} = \underline{\epsilon}_r\epsilon_0 = \epsilon' - j\epsilon''$ = complex permittivity of the medium in [F/m]
$\omega = 2\pi f$ = angular frequency of the signal in [rad/sec]
$j = \sqrt{-1}$ = imaginary unit

8.4.2 Intrinsic Impedance of Magnetic Lossless Media

If we neglected the magnetic losses ($\mu'' = 0$) and set the dielectric loss to $\epsilon'' = \sigma/\omega$, we can write the intrinsic impedance of a medium like this [2]:

$$\underline{\eta} = \sqrt{\frac{j\omega\mu'}{\sigma + j\omega\epsilon'}} \tag{8.8}$$

where,

$\omega = 2\pi f$ = angular frequency of the signal in [rad/sec]
$\mu' = \mu'_r \mu_0$ = permeability of the magnetic lossless medium in [H/m]
σ = specific conductance of the magnetic lossless medium in [S/m]
$\epsilon' = \epsilon'_r \epsilon_0$ = permittivity (dielectric constant) of the dielectric lossless medium in [F/m]
$j = \sqrt{-1}$ = imaginary unit

8.4.3 Intrinsic Impedance of Lossless Insulators

The calculation of the intrinsic impedance η [Ω] can even be more simplified for good insulators and lossless media ($\sigma \ll j\omega\epsilon'$) [2]:

$$\eta = \sqrt{\frac{\mu'}{\epsilon'}} \tag{8.9}$$

where,

$\mu' = \mu'_r \mu_0$ = permeability of the lossless media in [H/m]
$\epsilon' = \epsilon'_r \epsilon_0$ = permittivity (dielectric constant) of the lossless media in [F/m]

8.4.4 Intrinsic Impedance of Free-Space

For free space—where $\mu'_r = 1.0$ and $\epsilon'_r = 1.0$—the intrinsic impedance is [6]:

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 377\,\Omega \tag{8.10}$$

where,

$\mu_0 = 12.57 \cdot 10^{-7}$ H/m = permeability of vacuum, absolute permeability
$\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m = permittivity of vacuum, absolute permittivity

8.4.5 Intrinsic Impedance of Good Conductors

For waves traveling through (not along: through, e.g., through a shield) good conductors—where $\sigma \gg \epsilon_0\omega$—the intrinsic impedance is [6]:

$$\underline{\eta} = (1+j)\sqrt{\frac{\omega\mu'}{2\sigma}} = (1+j)\frac{1}{\delta\sigma} \tag{8.11}$$

where,

$\omega = 2\pi f$ = angular frequency of the signal in [rad/sec]
$\mu' = \mu'_r\mu_0$ = permeability of the conductive material in [H/m]
σ = specific conductance of the conductive material in [S/m]
$\delta = 1/\sqrt{\pi f \mu'_r \mu_0 \sigma}$ = skin depth in [m]

8.5 Wave Impedance Z_w

8.5.1 Wave Impedance of Any Wave

Generally, the ratio of the E-field [V/m] to the H-field [A/m]—for any electromagnetic wave—is the *wave impedance* $\underline{Z}_w$ [Ω]. Because of the vectorial character of the fields, the ratio must be defined in terms of the corresponding x-component $\underline{Z}_{wx}$ [Ω] and y-component $\underline{Z}_{wy}$ [Ω] of the $\underline{E}(z)$ [V/m] and $\underline{H}(z)$ [A/m] fields [3]:

$$\underline{Z}_{wx}(z) = \frac{\left[\overrightarrow{E}(z)\right]_x}{\left[\overrightarrow{H}(z) \times \overrightarrow{z}\right]_x} = \frac{\underline{E}_x(z)}{\underline{H}_y(z)} \tag{8.12}$$

$$\underline{Z}_{wy}(z) = \frac{\left[\overrightarrow{E}(z)\right]_y}{\left[\overrightarrow{H}(z) \times \overrightarrow{z}\right]_y} = -\frac{\underline{E}_y(z)}{\underline{H}_x(z)} \tag{8.13}$$

where,

$\overrightarrow{E}(z)$ = electric field vector traveling in z-direction in [V]
$\left[\overrightarrow{E}(z)\right]_x = \underline{E}_x(z)$ = electric field x-component of the wave traveling in z direction as complex phasor in [V]
$\left[\overrightarrow{E}(z)\right]_y = \underline{E}_y(z)$ = electric field y-component of the wave traveling in z direction as complex phasor in [V]
$\overrightarrow{H}(z)$ = magnetic field vector traveling in z-direction in [A/m]

$\left[\vec{H}(z) \times \vec{z}\right]_x = \underline{H}_y(z)$ = magnetic field y-component of the wave traveling in z direction as complex phasor in [A/m]
$\left[\vec{H}(z) \times \vec{z}\right]_y = \underline{H}_x(z)$ = magnetic field x-component of the wave traveling in z direction as complex phasor in [A/m]
$\vec{z}$ = unity vector in z-direction

The wave impedance of the x-component $\underline{Z}_{wx}(z)$ and y-component $\underline{Z}_{wy}(z)$ can also be written with respect to the intrinsic impedance of the medium $\underline{\eta}$ and the amplitudes E_{0x+} of the forward wave of the electric field x-component, E_{0y+} of the forward wave of the electric field y-component, E_{0x-} of the backward wave of the electric field x-component, and E_{0y-} of the backward wave of the electric field y-component [3]:

$$\underline{Z}_{wx}(z) = \frac{\underline{E}_x(z)}{\underline{H}_y(z)} = \underline{\eta}\frac{E_{0x+}e^{-\underline{\gamma}z} + E_{0x-}e^{\underline{\gamma}z}}{E_{0x+}e^{-\underline{\gamma}z} - E_{0x-}e^{\underline{\gamma}z}} \tag{8.14}$$

$$\underline{Z}_{wy}(z) = -\frac{\underline{E}_y(z)}{\underline{H}_x(z)} = -\underline{\eta}\frac{E_{0y+}e^{-\underline{\gamma}z} + E_{0y-}e^{\underline{\gamma}z}}{E_{0y+}e^{-\underline{\gamma}z} - E_{0y-}e^{\underline{\gamma}z}} \tag{8.15}$$

where,

$\underline{\gamma} = j\omega\sqrt{\underline{\mu}\underline{\epsilon}}$ = complex propagation constant in [1/m]
$\underline{E}_x(z) = E_{0x+}e^{-\underline{\gamma}z} + E_{0x-}e^{\underline{\gamma}z}$ = electric field x-component, propagating in z direction in [V/m]
$\underline{E}_y(z) = E_{0y+}e^{-\underline{\gamma}z} + E_{0y-}e^{\underline{\gamma}z}$ = electric field y-component, propagating in z direction in [V/m]
$\underline{H}_x(z) = -\frac{1}{\underline{\eta}}\left[E_{0y+}e^{-\underline{\gamma}z} - E_{0y-}e^{\underline{\gamma}z}\right]$ = magnetic field x-component, propagating in z direction in [A/m]
$\underline{H}_y(z) = \frac{1}{\underline{\eta}}\left[E_{0x+}e^{-\underline{\gamma}z} - E_{0x-}e^{\underline{\gamma}z}\right]$ = magnetic field y-component, propagating in z direction in [A/m]

8.5.2 Wave Impedance vs. Distance

Figure 8.3 shows the wave impedance $|\underline{Z}_w|$ [Ω] in dependency of the distance d [m] from the radiation source (normalized to the near-/far-field boundary). The graph is a simplification, and it should illustrate that magnetic field antennas and electric field antennas have different wave impedances in the near-field and that the electromagnetic field in the far-field has a constant wave impedance (for free space: $Z_w = \eta_0 \approx 377\,\Omega$).

The formulas in Sect. 8.5 showed that the general calculation of the wave impedance $\underline{Z}_w$ is complicated. However, this changes if we solely focus on the

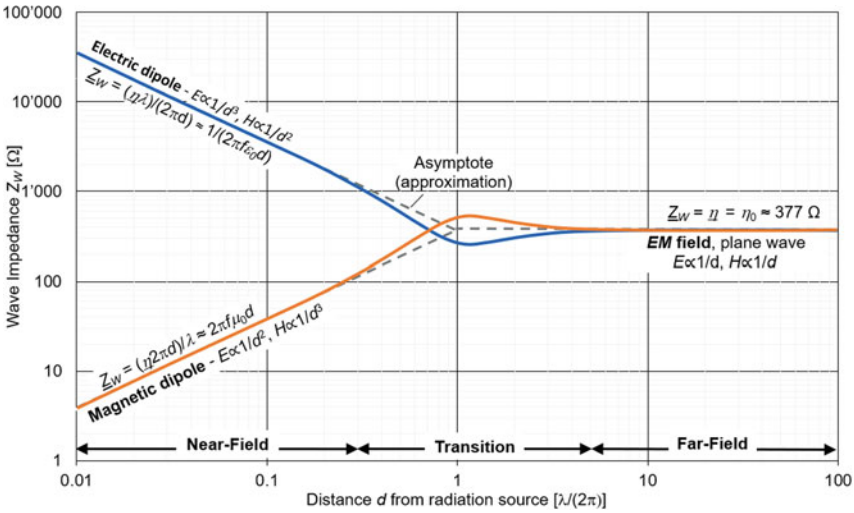

Fig. 8.3 Wave impedance $|\underline{Z}_w|$ vs. distance d from source (antenna)

far-field: in the far-field, the wave impedance is equal to the intrinsic impedance of the material through which the wave is propagating ($\underline{Z}_w = \underline{\eta}$).

In the near-field, the wave impedance depends primarily on the source. Electromagnetic waves are generated by two types of sources:

- **High-impedance sources, E-field antennas.** For high-impedance sources, the wave impedance $|\underline{Z}_w|$ [Ω] in the near-field is high and the E-field dominates. Examples of high-impedance sources are all kinds of wireless communication antennas (5G, Bluetooth, WiFi, RFID), radar antennas, and unintended antennas like cables, wires, and PCB traces. The frequency range of high-impedance antennas is very broad: from 10 kHz up to 100 GHz.
- **Low-impedance sources, H-field antennas.** For low-impedance sources, the wave impedance $|\underline{Z}_w|$ [Ω] in the near-field is low, and the H-field dominates. Examples of low-impedance sources are transformers, motors, inductors, coils, inductive charging systems, current loops, and all kinds of conductors with high currents. The frequency range of low-impedance antennas is typically not very broad: from 50 Hz (transformers) to several 100 kHz (inductive charging) up to 10 MHz (DC/DC converters).

8.5.3 Wave Impedance in the Near-Field of E-Field Antennas

The wave impedance $\underline{Z}_{we}$ [Ω] in the near-field of E-field antennas is approximately [5]:

$$\underline{Z}_{we} \approx -j\frac{\underline{\eta}}{\beta d} = -j\frac{\eta\lambda}{2\pi d} \tag{8.16}$$

where,

$\underline{Z}_{we}$ = wave impedance in the near-field of an E-field antenna in [Ω]
$\underline{\eta}$ = intrinsic impedance of media where wave is propagating through in [Ω]
$\beta = 2\pi/\lambda$ = phase constant (or phase factor) of the sinusoidal wave in [rad/m]
λ = wavelength of the sinusoidal wave in [m]
d = distance from the E-field antenna in [m]

In case of free space, where $\underline{\eta} = \eta_0 = \sqrt{\mu_0/\epsilon_0}$ and $\lambda = 1/(\sqrt{\mu_0\epsilon_0}f)$, the wave impedance in the near-field of E-field antennas can be simplified to [4]:

$$|Z_{we}| \approx \frac{1}{2\pi f\epsilon_r'\epsilon_0 d} = \frac{1}{2\pi f\epsilon_0 d} \tag{8.17}$$

where,

$|Z_{we}|$ = wave impedance in the near-field of a E-field antenna in [Ω]
f = frequency of the sinusoidal signal in [Hz]
ϵ_r' = relative electric permittivity of the medium in the near-field
$\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m = permittivity of vacuum, absolute permittivity
d = distance from the E-field antenna in [m]

8.5.4 Wave Impedance in the Near-Field of H-Field Antennas

The wave impedance $\underline{Z}_{wm}$ [Ω] in the near-field of H-field antennas is approximately [5]:

$$\underline{Z}_{wm} \approx -j\underline{\eta}\beta d = -j\frac{\underline{\eta}2\pi d}{\lambda} \tag{8.18}$$

where,

$\underline{Z}_{wm}$ = wave impedance in the near-field of a H-field antenna in [Ω]
$\underline{\eta}$ = intrinsic impedance of media where wave is propagating through in [Ω]
$\beta = 2\pi/\lambda$ = phase constant (or phase factor) of the sinusoidal wave in [rad/m]
λ = wavelength of the sinusoidal wave in [m]
d = distance from the H-field antenna in [m]

In case of free space, where $\underline{\eta} = \eta_0 = \sqrt{\mu_0/\epsilon_0})$ and $\lambda = 1/(\sqrt{\mu_0\epsilon_0}f)$, the wave impedance in the near-field of H-field antennas can be simplified to [4]:

$$|Z_{wm}| \approx 2\pi f\mu_r'\mu_0 d = 2\pi f\mu_0 d \tag{8.19}$$

where,

$|Z_{wm}|$ = wave impedance in the near-field of a H-field antenna in [Ω]
f = frequency of the sinusoidal signal in [Hz]
μ'_r = relative magnetic permeability of the medium in the near-field
$\mu_0 = 12.57 \cdot 10^{-7}$ H/m = permeability of vacuum, absolute permeability
d = distance from the H-field antenna in [m]

8.5.5 *Wave Impedance of Plane Waves*

For plane waves—meaning electromagnetic waves in the far-field—the wave impedance $\underline{Z}_w$ [Ω] is equal to the intrinsic impedance $\underline{\eta}$ [Ω] of the medium:

$$\underline{Z}_w = \underline{\eta} \tag{8.20}$$

In case of free space, the wave impedance is simply:

$$Z_w = \eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \approx 377\,\Omega \tag{8.21}$$

where,

$\mu_0 = 12.57 \cdot 10^{-7}$ H/m = permeability of vacuum, absolute permeability
$\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m = permittivity of vacuum, absolute permittivity

8.6 Summary

- **Electromagnetic field.** The electromagnetic field can be viewed as an interdependent time-varying field consisting of an electric field E and magnetic field H, propagating in the same direction.
- **Near- and far-field.** The area around an antenna can be divided into three regions: reactive near-field, radiative near-field, and far-field (Table 8.1).
  - **Electrically small antennas D $< \lambda/(2\pi)$.** Roughly speaking, only the reactive near-field is significant for electrically small antennas. It extends from the antenna to the distance $d_{reactive-near-field}$:

$$d_{reactive-near-field} = 0 \ldots \frac{\lambda}{2\pi} \tag{8.22}$$

where,

λ = wavelength of the sinusoidal signal in [m]

Table 8.1 Comparison of two criteria (Rayleigh and Maxwell) for the near-field to far-field transition for various frequencies f [Hz] and maximum antenna dimensions D [m]

Frequency	$\lambda/2$ [m]	Maximum dimension D [m]	Raylegh $d = 2D^2/\lambda$ [m]	Maxwell $d = \lambda/(2\pi)$ [m]
30 MHz	5	10	20	1.59
30 MHz	5	2	0.8	1.59
100 MHz	1.5	3	6	0.48
100 MHz	1.5	0.5	0.17	0.48
300 MHz	0.5	1	2	0.16
300 MHz	0.5	0.1	0.02	0.16
1 GHz	0.15	0.3	0.6	0.05
1 GHz	0.15	0.05	0.017	0.05
3 GHz	0.05	0.1	0.2	0.02
3 GHz	0.05	0.02	0.008	0.02
6 GHz	0.025	0.05	0.1	0.01
6 GHz	0.025	0.01	0.004	0.01

– **Electrically large antennas D $> \lambda/(2\pi)$.** For electrically large antennas, all three regions are significant.

$$d_{reactive-near-field} = 0 \ldots 0.62\sqrt{\frac{D^3}{\lambda}} \tag{8.23}$$

$$d_{radiating-near-field} = 0.62\sqrt{\frac{D^3}{\lambda}} \ldots \frac{2D^2}{\lambda} \tag{8.24}$$

$$d_{far-field} > \frac{2D^2}{\lambda} \tag{8.25}$$

where,

λ = wavelength of the sinusoidal signal in [m]
D = maximum linear dimension of the antenna in [m]. $D = l$ for a wire antenna.

- **Intrinsic impedance $\underline{\eta}$.** The intrinsic impedance $\underline{\eta}$ depends only on the properties of the material (conductivity, permeability, permittivity), and for plane waves, the wave impedance $\underline{Z}_w$ is equal to the intrinsic impedance.

$$\underline{\eta} = \sqrt{\frac{\underline{\underline{\mu}}}{\underline{\epsilon}}} \tag{8.26}$$

where,

$\underline{\mu} = \mu' - j\mu''$ = complex permeability of the media through which the electromagnetic wave is propagating in [H/m]
$\underline{\epsilon} = \epsilon' - j\epsilon''$ = complex permittivity of the media through which the electromagnetic wave is propagating in [F/m]

- **Wave impedance $\underline{\mathbf{Z}}_{\mathbf{w}}$.** The wave impedance is a characteristic of a particular wave (which depends on the source antenna, the material, the frequency, etc.). For plane waves, we get:

$$\underline{Z}_w = \underline{\eta} \tag{8.27}$$

where,

$\underline{\eta}$ = intrinsic impedance of the material through which the electromagnetic wave is propagating in [Ω]

And for plane waves in free space, we get:

$$Z_w = \eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377\,\Omega \tag{8.28}$$

where,

$\mu_0 = 12.57 \cdot 10^{-7}$ H/m = permeability of vacuum, absolute permeability
$\epsilon_0 = 8.854 \cdot 10^{-12}$ F/m = permittivity of vacuum, absolute permittivity

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