Understanding EMC Basics Part 1:
EM Field Theory and Three Types of EM Analysis
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Contents of Webinar #1
1. Electromagnetic fields, waves, and the importance of the return current path
2. Field theory, permittivity, permeability, wave impedance and velocity
3. Near-field and Far-field
4. Three types of EMC analysis (includes Skin Effect)

Electromagnetic (EM) fields
- Every non-DC voltage/current is a wave of propagating EM energy...
  - guided by send and return current paths
    - and the insulators (dielectrics) that surround them (e.g. air)
- EM waves spread out and create EM fields, (like ripples spreading out and making a pattern on a pool)...
  - and we measure fields in terms of field strength
- Design for EMC is mostly about controlling fields
  - so that they are high where we want power or signals
  - and low where we don’t want emissions or susceptibility

Of course, a wave has different amplitudes along its path
- When a conductor is long enough
  - it cannot experience the same voltage or current, at the same time, over its whole length...
    - which is why high frequencies seem to behave so weirdly!
- The ratio between wavelength ($\lambda$) and conductor dimension is very important
  - we can usually ignore “wave effects” when the dimension we are concerned with is $<1/100^{th}$ of the $\lambda$...
    - e.g. at 1GHz:
      - $<3mm$ in air ($\lambda = 300mm$); $<1.5mm$ in FR4 ($\lambda = 150mm$)
Importance of the return current path

- Electric and magnetic fields are the true nature of electrical and electronic power and signals
  - and they both depend on the physical routes taken by the send and return currents
- A great deal of EMC design depends on controlling the paths of the return currents
- All currents always flow in complete loops...
  - taking the path of least impedance – the path with the least area – i.e. the return current flows as close to its send path as it is allowed to

We don’t need field theory – just a few concepts

- Fluctuating voltages create Electric fields (E)
  - which are measured in Volts/metre (V/m)
- Fluctuating currents create Magnetic fields (H)
  - which are measured in Amps/metre (A/m)
- EM waves have power (P)
  - measured in Watts/square metre (W/m²)
    (i.e. the rate at which energy passes through an area)

Permeability (µ) and permittivity (ε)

- All media or materials have conductivity/resistivity (i.e. loss of EM energy, turned into heat), µ and ε...
  - in vacuum (and air): $\mu_0 = 4\pi \times 10^{-7}$ Henries/metre...
    - i.e. the vacuum can contain magnetic field energy
  - And: $\varepsilon_0 = (1/36\pi) \times 10^{9}$ Farads/metre
    - i.e. the vacuum can also contain electric field energy
- Other media and materials are characterised by their relative permeability ($\mu_R$) and permittivity ($\varepsilon_R$)
  - so their absolute permeability is: $\mu_0\mu_R$
  - and their absolute permittivity is: $\varepsilon_0\varepsilon_R$

Permeability (µ) and permittivity (ε) continued...

- In conductors (e.g. wires, PCB traces): µ and ε are what causes them to have inductance (L) and capacitance (C)...
  - so whenever there is a fluctuating voltage (V) there is always an associated current (I), and vice-versa
- In insulators (e.g. PVC, FR4, air): µ and ε cause effects similar to inductance and capacitance...
  - so whenever there is a fluctuating electric field (E) there is always an associated magnetic field (H), and vice-versa

µ and ε govern an EM wave’s impedance, and it’s propagation velocity

- For the wave’s ‘far field’ impedance ...
  $Z = \frac{E}{H} = \frac{V}{A/m} = \sqrt{(\mu_0\mu_R/\varepsilon_0\varepsilon_R)} \ \Omega$
  $Z = 377\Omega$ in air or vacuum
  $Z = 377\sqrt{(\mu_R/\varepsilon_R)}$ in a medium or material
- For the velocity of the wave’s propagation ...
  $v = \frac{1}{\sqrt{(\mu_0\mu_R\varepsilon_0\varepsilon_R)}} \ \text{metres/second}$
  $v = 3.10^8 \text{m/s}$ in air or vacuum (i.e. the speed of light)
  $v = 3.10^8\sqrt{(\mu_R\varepsilon_R)} \ \text{m/s}$ in a medium or material
And the velocity of wave propagation \( (v) \) links frequency \( (f) \) to wavelength \( (\lambda) \)

\[ v = f \lambda \]

- In vacuum or air: \( v = c = 300 \text{ million metres/second} \)
  - \( 1/\sqrt{\mu_0 \varepsilon_0} \), equivalent to 3ns/metre, 3ps/millimetre
- But in media or materials with \( \mu_R \) and/or \( \varepsilon_R > 1.0 \), \( v \) is slower than \( c \)
  - so the wavelength \( (\lambda) \) is shorter (for a given \( f \))
  - e.g. for a printed-circuit board trace, \( v \) is approx. 50% of \( c \)
  - ...so a \( \lambda \) is approx. 50% of what it would be in air

**Understanding EMC Basics**

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Near Field and Far Field

Near-field and Far-field

- Near fluctuating voltages or currents, E and H fields have complex patterns: field strengths vary as \( 1/r^3, 1/r^2 \) and \( 1/r \)
  - where \( r \) is the radial distance from the source
  - because of stray capacitance and stray mutual inductance effects (i.e. E and H field coupling)
- But, far enough away, the fields become EM waves (E and H fields in the ratio of the wave impedance: \( Z \))...
  - and have simple ‘plane wave’ spherical distributions with field strengths that vary as \( 1/r \)

Near-field and Far-field continued...

- For sources with longest dimensions \(<<\lambda\), the boundary between the near and far field regions is:
  \[ r = \lambda/2\pi \]
- But for sources with dimensions \(>\lambda\), the near/far field boundary is:
  \[ r = 2D^2/\lambda \]
  - where \( D \) is the largest dimension of the source

Near-field and far-field when the source's largest dimension is \(<<\lambda\) (for illustration only)

**An example of a near-field field distribution**

This simulation is of a heatsink in free space – proximity to enclosure will have an effect

This shows the fields in one plane at 3.25GHz, but the simulator calculates all of the frequencies in all of the three dimensions

Near (induction) field

EM fields (also called plane waves, which vary as \( 1/r \))

The final value of the wave impedance depends on the medium it is propagating through (e.g. 377\( \Omega \) in vacuum / air)

**Wave impedance \( \Omega \)**

- Near (induction) field (fields vary as \( 1/r^3, 1/r^2 \) and \( 1/r \))
  - E field source
  - H field source
- Far (radiation) field
  - 377\( \Omega \) in vacuum / air

**Radial distance \( (r) \) from source in units of \( \lambda/2\pi \)**

- 0.1 0.2 0.3 0.5 1 2 3 5

**Frequency 8.31±1p1GHz Only**

- 0 1 10 20 50 100 200 500 1000 2000 5000 10000

- 1 7.82 10 21.82 24 36 48 60 77 90 110

- 1 7.82 10 21.82 24 36 48 60 77 90 110

- 1 7.82 10 21.82 24 36 48 60 77 90 110

- 1 7.82 10 21.82 24 36 48 60 77 90 110

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- 1 7.82 10 21.82 24 36 48 60 77 90 110
Poll Questions

Understanding EMC Basics

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Three types of EMC analysis
(includes Skin Effect)

EMC uses three types of analysis

- For conductor dimensions < \(\lambda/6\) we can use ‘lumped circuit analysis’ methods (based on R, L, C)
- When conductor dimension is > \(\lambda/6\) along one axis (e.g. a wire) we must use ‘transmission line’ analysis
- But when conductors are > \(\lambda/6\) in two or three dimensions we must use ‘full-wave analysis’
  - based on Maxwell’s Equations
  - only practical for very simple situations, or when using computers to do the analysis

Resonances

- All circuits have RF resonant modes
  - where their currents or voltages experience resonant gain, called their ‘Q factor’...
  - Qs of 100 or more are common (i.e. gains of 40dB or more)
- As the voltage peaks, the current nulls, and vice-versa (to maintain a constant energy as the wave propagates)
- High levels of emissions (and poor immunity) tend to occur at resonances...
  - so we often need to control them to achieve EMC

Lumped analysis...

Everything has resistance (R), inductance (L), and capacitance (C)

- including all components, wires, cables, PCB tracks, connectors, silicon metallisation, bond wires, etc
- also including their ‘stray’ or ‘parasitic’ Rs, Ls, and Cs
  - which can be intrinsic (e.g. the self-inductance of a wire lead)
  - or extrinsic (e.g. stray C or L coupling due to proximity to other objects)
- Resistance increases with \(f\) due to Skin Effect

Lumped analysis:

Resistance and Skin Effect

- DC currents travel through the whole cross-sectional area of a conductor
  - but AC currents are forced to flow close to the surface
- This is known as the “skin effect”
- So, high-frequency currents only penetrate weakly into the depth (thickness) of a conductor
  - increasing the resistance in their path
Examples of cross-sectional current density in a copper sheet

- Example at d.c: Uniform current density (Vdc)
- Example of surface currents at 1MHz: (δ = 0.07mm) (Vac)

Resistance and Skin effect continued...

- One skin depth (δ) is the depth into the conductor by which the current density has reduced to 1/e
  \[ \delta = \frac{1}{\sqrt{\pi \sigma \mu_0 \mu_r}} \text{ metres} \]
  - where \( \sigma \) = conductivity
- For copper conductors: \( \delta = \frac{66}{\sqrt{f}} \) (\( f \) in Hz gives \( \delta \) in millimetres)
  - e.g. at 160MHz \( \delta = 0.005\text{mm} \), so 0.05mm below the surface (10 skin depths) the current density is negligible

Graph of skin depth (δ) for copper, aluminium, and mild steel

- Skin depth (in mm)
- 100
- 10
- 1
- 0.1
- 0.01
- 0.001
- 0.0001
- 0.00001
- 100
- 10
- 1
- 0.1
- 0.01
- 0.001
- 0.0001
- 0.00001

Lumped analysis: Stray Inductance

- E.g. a thin wire has self-inductance of about 1µH per metre (1nH per mm)
  - this assumes its return current path is very far away
  - a close return path reduces the overall inductance experienced by the send/return current
- Close proximity to ferromagnetic materials (e.g. steel) with \( \mu_r > 1 \) will increase its self-inductance
- But close proximity to conductors (e.g. cables, metalwork, etc.) will decrease self-inductance

Lumped analysis: Stray Capacitance

- E.g. a thin wire on its own in free space has about 40pF per metre length (approx. 0.04pF per mm)....
  - this is its ‘space charge’ capacitance....
  - close proximity to dielectrics (\( \varepsilon_r > 1 \)) will add more stray space charge capacitance
- Proximity of conductors adds stray capacitance...
  - (8.8/\( d \)) nF/square metre in air (\( d \) is the spacing in mm)
  - (8.8 \( \varepsilon_r/d \)) nF/sq. m., when \( d \) is the spacing through insulation

Lumped Analysis: Resonances

- L and C store energy in their E and H fields
  - this is true for intentional Ls and Cs (e.g. components) and ‘stray’ or ‘parasitic’ Ls and Cs
- All types of circuits have L and C (even if they are only strays) and these cause resonances, at:
  \[ f_{\text{RES}} = \frac{1}{2\pi \sqrt{LC}} \]
- These resonances are ‘damped’ by the resistances in the circuit
Transmission line analysis...
all send/return conductors have characteristic impedance (called $Z_0$)

- The L and C associated with a small length governs the velocity ($v$) with which EM waves travel through that length...
  \[ v = \frac{1}{\sqrt{LC}} \]
- And the ratio of the L to the C governs the characteristic impedance ($Z_0$) of that length...
  \[ Z_0 = \sqrt{\frac{L}{C}} \]
- Note: the L and C values used in the above expressions are 'per unit length' (e.g. 1µH/metre, 100pF/metre) where the unit lengths used are shorter than $\lambda/6$

The effects of keeping $Z_0$ constant

- If $Z_0$ is kept constant from source to load, almost 100% of the wave (= signal) is communicated
  - which means that there must be low emissions from the wanted signal (because there is very little energy lost)
- This is called matched transmission line design
  - and a matched transmission line is a very inefficient antenna
    - which is why all general purpose RF test equipment has 50Ω inputs and outputs, connected with '50Ω cable'

Changes in $Z_0$ over dimensions greater than $\lambda/6$

- These cause propagating EM waves to be reflected (whether they are signals or power)
  - like the ripples spreading in a pool of water reflecting from a floating stick
- The technique called “EMC filtering” relies upon creating changes in characteristic impedance
  - to reflect unwanted noise away from a protected circuit

Transmission-line analysis: Resonances

- When a conductor has the same type of $Z_0$ discontinuity at each end (whether the source and load impedances are both too high, or too low)...
  - resonances occur when conductor length is a whole number of half-wavelengths...
    \[ f_{\text{res}} = 150 \frac{1}{L} \text{ (air dielectric)} \]
    where $i$ is an integer (1, 2, 3, etc.), $L$ is conductor length (metres) and $f_{\text{res}}$ is in MHz

Transmission-line analysis: Resonances
continued...

- When a conductor has opposing types of $Z_0$ discontinuity at its ends...
  - resonances occur when conductor length is an odd number of quarter-wavelengths...
    \[ f_{\text{res}} = 75 \frac{1}{L} \text{ (air dielectric)} \]
    where $i$ is an odd-numbered integer (1, 3, 5, etc.), $L$ is conductor length (metres) and $f_{\text{res}}$ is in MHz

2-dimensional structural resonances: 'standing waves' caused by reflections at the edges of a metal plate

- Resonances can only occur at integer multiples of half-wavelengths, at:
  \[ f_{\text{res}} = 150 \sqrt{\left(\frac{i}{L}\right)^2 + \left(\frac{m}{W}\right)^2} \text{ (in MHz)} \]
  - where: $i$ and $m$ are integers (0, 1, 2, 3, etc.)
    - and $L$ and $W$ are the plate’s length and width (in metres)
‘Standing waves’ caused by reflections at the edges of a metal plate

Magnetic field standing waves must have minima at the edges of the metal plate (air has much higher impedance than metal)…

– whilst electric fields must be a maximum at the edges

Resonances can only occur at integer multiples of half-wavelengths, at:

\[ f_{\text{res}} = 150 \sqrt{(l/L)^2 + (m/W)^2 + (n/H)^2} \] (in MHz)

where: \( l, m, n \) are integers (0, 1, 2, 3, etc.)

and \( L, W, H \) are the box’s length, width, height (in metres)

A FLO/EMC simulation of the electric field distribution inside a shielded box

The simulator calculates all frequencies, in three dimensions. This figure shows a ‘slice’ through a box at one of its resonant frequencies – probably the \((3,0,0)\) mode

Notice the field ‘leaking’ out through an aperture

Poll Questions