Chapter 1

Introduction to Electromagnetic Compatibility

National Taiwan University of Science and Technology

Chun-Long Wang

Outline

- Preview
- Aspects of EMC
- History of EMC
- Examples
- Electrical Dimensions and Waves
- Decibels and Common EMC Units

Preview

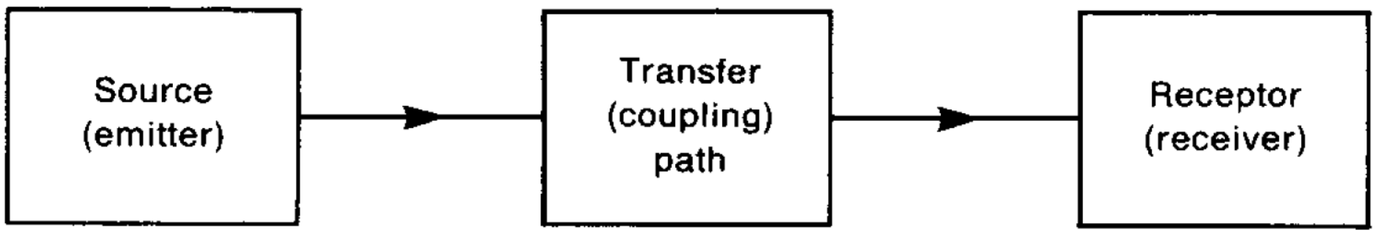
- Category of Receiver Interference
  - Intentional Receiver
    - The reader has no doubt experienced noise produced in an AM radio by nearby lightning discharges. Also, even though the radio may not be tuned to a particular transmitter frequency, the transmission may be received, causing the reception of an unintended signal.
  - Unintentional Receiver
    - A digital computer may pick up a strong transmission from an FM radio station or TV station.
    - Conversely, the digital computer may create emissions that couple into a TV (other than the antenna), causing interference.

Preview

- Basic Description of EMC
  - Definition of EMC
    - An electronic system is said to be electromagnetically compatible with its environment if it does not produce or be susceptible to interference. (It may couple signal into the system, but does not cause interference.)
  - Criteria of EMC
    - It does not cause interference with other systems.
    - It is not susceptible to emissions from other system.
    - It does not cause interference with itself.

Aspects of EMC

- Basic Decomposition of EMC Coupling
  - Definition
    - EMC is concerned with the generation, transmission, and reception of electromagnetic energy.



    - Interference occurs if the received energy causes the receptor to behave in an undesired manner.
    - Unintentional transmission or reception is not necessarily detrimental; undesired behavior of the receptor constitutes interference.

Aspects of EMC

- Basic Decomposition of EMC Coupling
  - Ways to Prevent Interference

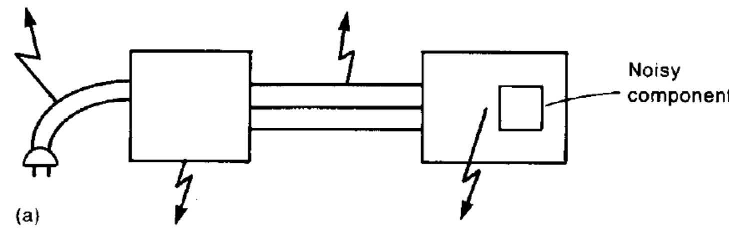
1. Suppress the emission at its source.
2. Make the coupling path as inefficient as possible for the noise.
3. Make the receptor less susceptible to the emission.

Working from step 1 to step 3, success will usually be easier to achieve and with less additional design cost.
The most simplest way is to put all the electronic products in a metallic enclosure with internal batteries, but this costs a lot.

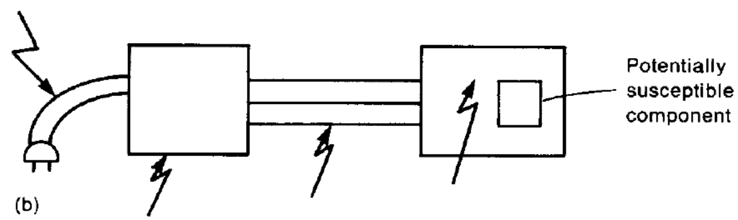
Aspects of EMC

- Basic EMC Subproblems
  - Transfer of Electromagnetic Energy

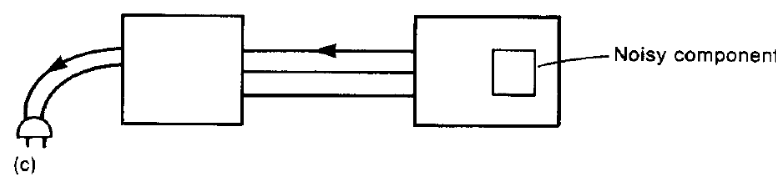
1. Radiated emissions



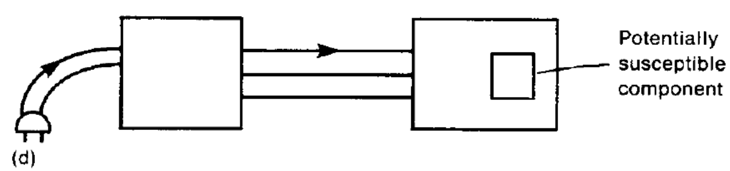
2. Radiated susceptibility



3. Conducted emissions



4. Conducted susceptibility

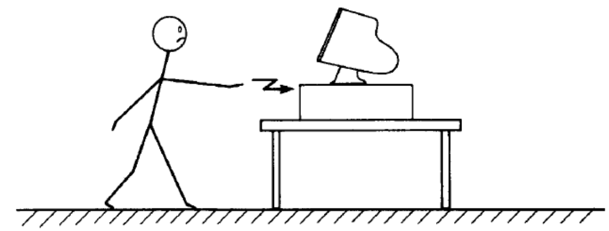


Aspects of EMC

- Basic EMC Subproblems
  - Importance of Power Net
    - Although the primary intent of the power cable is to transfer 60 Hz commercial power to the system, it is important to realize that other much higher-frequency signals may and usually do exist on the ac power cord.
    - These higher-frequency signals may interfere with other system via conduction or radiation. Thus, reducing the interference from the power net is a important topic of EMC problems.

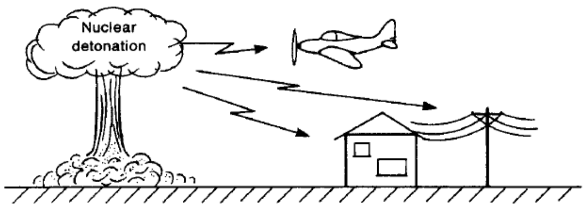
Aspects of EMC

- Other Aspects of EMC
  - Examples
    1. Electrostatic discharge (ESD)



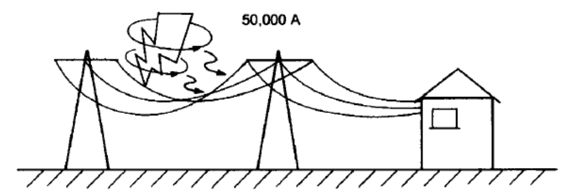
(a)

    2. Electromagnetic pulse (EMP)



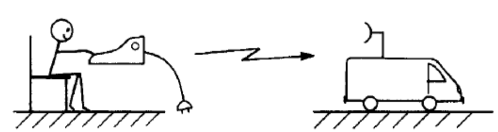
(b)

    3. Lightning



(c)

    4. TEMPEST



(d)

These problems are not restricted by the government, but needed to be concerned with during the design process.

Aspects of EMC

- Solutions for EMC
  - Mathematical Model
    - The primary vehicle used to understand the effects of interference is a mathematical model.
    - The criterion that determines whether the model adequately represents the phenomenon is whether it can be used to predict experimentally observed results.
    - Once the model is established, we can use it to predict future events in the design process of a circuit or system such that the design costs could be reduced.

History of EMC

- Organizations
  - Europe
    - The International Special Committee on Radio Interference (CISPR): In 1933, the committee produced a document detailing measurement equipment for determining potential EMI emissions.
  - USA
    - The Federal Communications Commission (FCC): published a regulation in 1979 that required the electromagnetic emissions of all "digital devices" to be below certain limits.
    - The military sets a regulation of a susceptibility requirement.

Examples

- Events in the Textbook
  - Motor of Electric Equipment → Spark-Gap → Power Cord → TV Antenna → TV Screen
  - Making a Copy on a Copying Machine → DC Current → Power Cord → Power Net → Hall Clock Reset
  - Illegal FM Radio Transmitter → Microprocessor-Controlled Emission and Fuel Monitoring System Shut Down.
  - Citizens Band (CB) Transmitter → Breaking System of a Car Locked Up.

Examples

- Events in the Textbook
  - Surveillance Radar in an Airport → Computer Systems Lose Data or Store Incorrect Data
  - Falkland Battle (1982): the U.K. Lost a Destroyer (Communication System ←→ Antimissile Detection System)
  - Electromagnetic Emissions → Helicopter's Electronically Controlled Flight Control System → The U.S. Army Lost Helicopters (UH-60 Black Hawk)
  - The Ship's High-Power Search Radar → RF Voltages → Inadvertently Deployment of a Missile

Examples

- Daily Life Events
  - Mobile Phones
    - While the mobile phone connects with the base station, the electromagnetic wave is the strongest at that time. This wave would interfere with the speaker to produce noisy sound or with the CRT monitor to produce noisy signal on it.
  - Radio Stations
    - When we drive across two different areas, we could feel that our favorite radio station is disturbed by local stations.

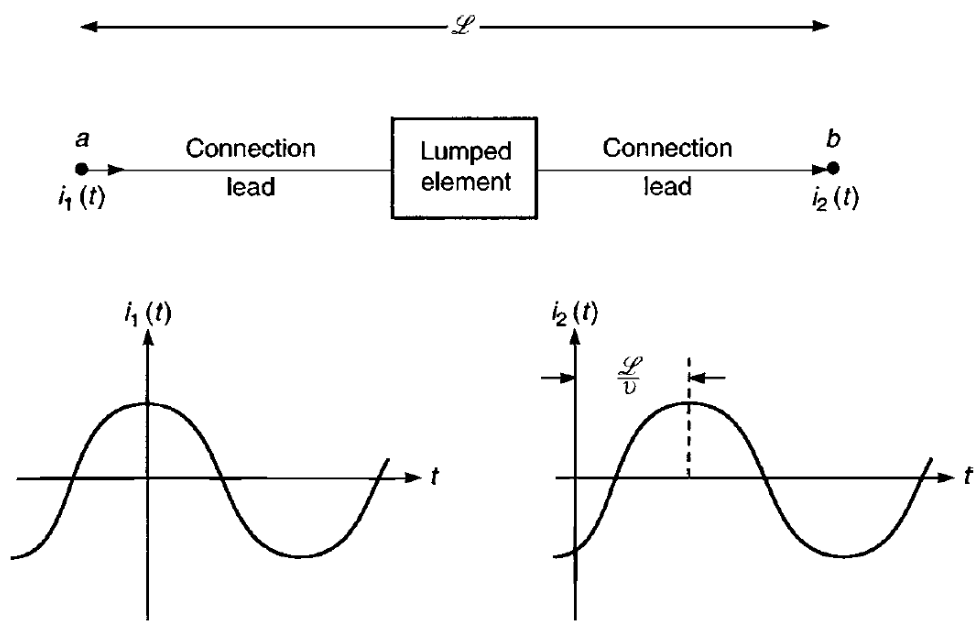
Electrical Dimensions and Waves

- Electrical Dimensions
  - Notes
    - Electrical dimensions of the structure in wavelengths are more significant in determining the ability of that structure to radiate electromagnetic energy.
    - If the electrical dimensions are small as compared to 1/10 wavelengths, lumped elements and circuit theory could be used to solve the problem without adopting the mathematically complex Maxwell's equations.
    - If the electrical dimensions are large as compared to wavelengths, Maxwell's equations must be used.

Electrical Dimensions and Waves

- Effect of Element Interconnection Leads
  - Time Delay
    - The time delay for a wave propagating from node a to node b is

$$T_D = \frac{\mathscr{L}}{v} \quad \text{s}$$



Observing the phase difference between nodes a and b while L is electrically large or small.

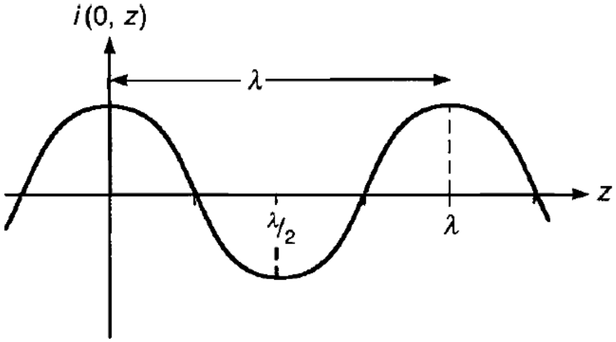
Electrical Dimensions and Waves

- Phase Difference and Electrical Length
  - Phase Difference
    - Supposing a sinusoidal propagating wave

$$i(z,t) = I\cos(\omega t - \beta z)$$

    - where β is the phase constant and ω is the radian frequency, thus for wave traveling a length *L*, we have a phase difference of

$$\phi = \beta \mathscr{L} \quad \text{radians}$$



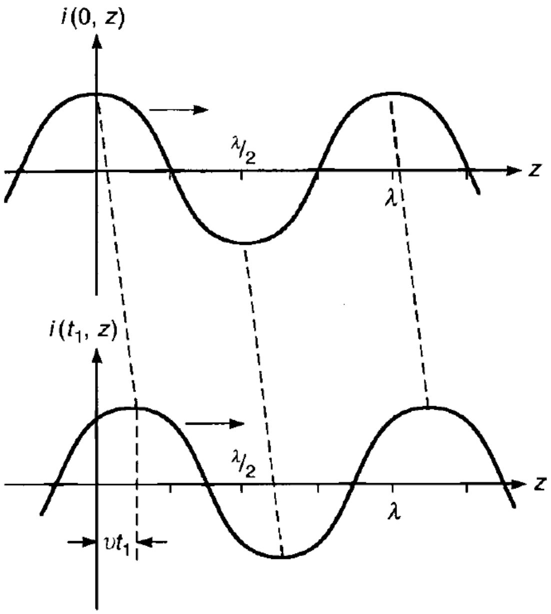
  - Electrical Length
    - Since $\beta\lambda = 2\pi \quad \text{radians}$
    - The phase difference could be rewritten as a form of electrical length $i(z,t) = I\cos\left(\omega t - 2\pi\frac{z}{\lambda}\right)$

Electrical Dimensions and Waves

- Phase Difference and Time Delay
  - Time Delay
    - Since $\omega t - \beta z = \text{constant}$
    - we know that as t increases, z must increases, thus this wave is propagating in the +z direction.
    - The phase velocity is given by

$$v = \frac{dz}{dt} = \frac{\omega}{\beta} = \lambda f \quad \text{m/s}$$

$$\lambda = \frac{v}{f} \quad \text{m}$$



Electrical Dimensions and Waves

- Phase Difference and Time Delay
  - Time Delay
    - Thus, the current could be rewritten as a form of phase delay

$$i(z,t) = I\cos\left(\omega\left(t - \frac{\beta}{\omega}z\right)\right)$$
$$= I\cos\left(\omega\left(t - \frac{z}{v}\right)\right)$$

    - We can see that the phase shift of a wave is equivalent to the time delay, which is given by z/v seconds.

Electrical Dimensions and Waves

- Phase Velocity
  - Definition
    - The phase velocity is defined as

$$v = \frac{1}{\sqrt{\epsilon\mu}} = \frac{v_0}{\sqrt{\epsilon_r\mu_r}}$$

We see that the velocity would be smaller while the wave is propagating in a denser medium, i.e. a larger value of ε_r

- where v_0 is the velocity in free space

$$v_0 = \frac{1}{\sqrt{\epsilon_0\mu_0}} = 3 \times 10^8 \text{ m/s} \quad \text{(approximate)}$$

$$\epsilon_0 = \frac{1}{36\pi} \times 10^{-9} \text{ F/m} \quad \text{(approximate)}$$ Permittivity

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m} \quad \text{(exact)}$$ Permeability

Electrical Dimensions and Waves

Frequency (f)	Wavelength (λ)
60 Hz	3107 miles (5000 km)
3 kHz	100 km
30 kHz	10 km
300 kHz	1 km
3 MHz	100 m
30 MHz	10 m
300 MHz	**1 m**
3 GHz	10 cm
30 GHz	1 cm
300 GHz	1 mm

- Waves in Denser Medium
  - Definition
    - Since the wavelength is defined as

$$\lambda = \frac{v}{f}$$

$$= \frac{v_0}{f\sqrt{\epsilon_r \mu_r}} = \frac{\lambda_0}{\sqrt{\epsilon_r \mu_r}}$$

We see that the wavelength λ is smaller while the wave is propagating in a denser medium, i.e. a larger value of ε_r

- And the electrical dimension of a circuit is defined as

$$k = \frac{\mathscr{L}}{\lambda}$$

- We could see that for a denser medium, the velocity v_0 is smaller, thus the wavelength λ is smaller, and the electrical dimension k would be larger.

Electrical Dimensions and Waves

- Frequencies and Corresponding Wavelengths of Electronic Systems

Frequency Band[a]	Wavelength	Uses
EHF (30–300 GHz)	1 cm–1 mm	Radar, remote sensing, radio astronomy
SHF (3–30 GHz)	10 cm–1 cm	Radar, satellite communication, remote sensing, microwave electronic circuits, aircraft navigation, **digital systems**
UHF (300–3000 MHz)	1 m–10 cm	Radar, TV, microwave ovens, air navigation, cell phones, military air traffic control communication and navigation, **digital systems**
VHF (30–300 MHz)	10 m–1 m	TV, FM broadcasting, police radio, mobile radio, commercial air traffic control (ATC) communication and navigation, **digital systems**
HF (3–30 MHz)	100 m–10 m	Shortwave radio (ham), citizens band
MF (300–3000 kHz)	1 km–100 m	AM broadcasting, maritime radio, ADF direction finding
LF (30–300 kHz)	10 km–1 km	Loran long-range navigation, ADF radio beacons, weather broadcasting
VLF (3–30 kHz)	100 km–10 km	Long-range navigation, sonar
ULF (300–3 kHz)	1 Mm–100 km	Telephone audio range
SLF (30–300 Hz)	6214 mi–621 mi	Communication with submarines, commercial power (60 Hz)
ELF (3–30 Hz)	62,137 mi–6214 mi	Detection of buried metal objects

[a]E = extra, S = super, U = ultra, V = very, H = high, M = medium, L = low, F = frequency.

Knowing the spectrum distribution of the electronic systems will help you specify the source of the interference.

Electrical Dimensions and Waves

- Relative Permittivities of Various Dielectrics

Material	ϵ_r
Air	1.0005
Styrofoam	1.03
Polyethylene foam	1.6
Cellular polyethylene	1.8
Teflon	2.1
Polyethylene	2.3
Polystyrene	2.5
Nylon	3.5
Silicon rubber	3.1
Polyvinyl chloride (PVC)	3.5
Epoxy resin	3.6
Quartz (fused)	3.8
Epoxy glass (printed circuit substrate)	4.7
Bakelite	4.9
Glass (pyrex)	5.0
Mylar	4.0
Porcelain	6.0
Neoprene	6.7
Polyurethane	7.0
Silicon	12.0

Electrical Dimensions and Waves

- Relative Permeabilities and Conductivities (Relative to Copper) of Various Metals

Conductor	σ_r	μ_r
Silver	1.05	1
Copper-annealed	1.00	1
Gold	0.70	1
Aluminum	0.61	1
Brass	0.26	1
Nickel	0.20	600
Bronze	0.18	1
Tin	0.15	1
Steel (SAE 1045)	0.10	1000
Lead	0.08	1
Monel	0.04	1
Stainless Steel (430)	0.02	500
Zinc	0.32	1
Iron	0.17	1000
Beryllium	0.10	1
Mumetal (at 1 kHz)	0.03	30,000
Permalloy (at 1 kHz)	0.03	80,000

Decibels and Common EMC Units

- Power and Voltage (Current) Gains
  - Definition for Power Gain
    - The power gain is defined as

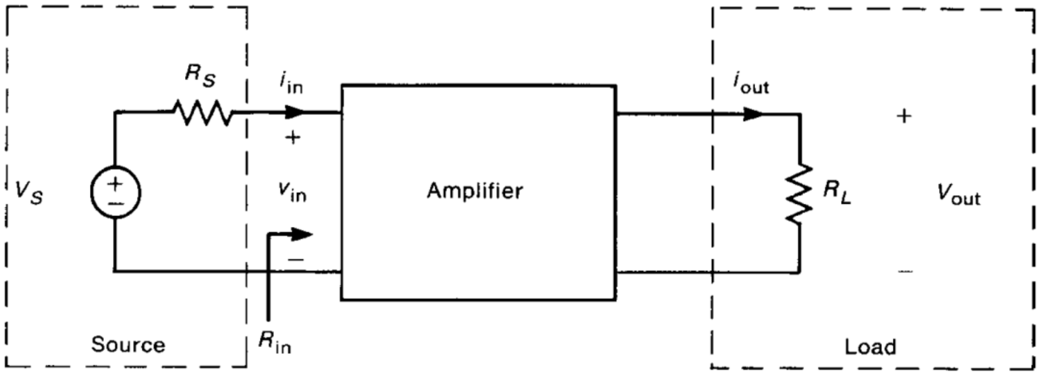
$$\frac{P_{out}}{P_{in}} = \frac{v_{out}^2}{v_{in}^2}\frac{R_{in}}{R_L}$$

    - where the input and output powers are defined as

$$P_{in} = \frac{v_{in}^2}{R_{in}} \qquad P_{out} = \frac{v_{out}^2}{R_L}$$

    - Thus the power gain expressed in decibels is defined as

$$10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$



Decibels and Common EMC Units

- Power and Voltage (Current) Gains
  - Definition for Voltage and Current Gains
    - The voltage and current gains are defined as

$$\text{Voltage gain} = \frac{v_{\text{out}}}{v_{\text{in}}} \qquad \text{Current gain} = \frac{i_{\text{out}}}{i_{\text{in}}}$$

    - In dB, these are defined as

$$20 \log_{10}\left(\frac{v_{\text{out}}}{v_{\text{in}}}\right) \qquad 20 \log_{10}\left(\frac{i_{\text{out}}}{i_{\text{in}}}\right)$$

    - When $R_{in}=R_L$

$$\text{Power gain} = 20 \log_{10}\left(\frac{v_{\text{out}}}{v_{\text{in}}}\right)_{R_L=R_{\text{in}}}$$

    - which is the same as the voltage gain
    - also, it is equal to the current gain via the definition of $P=i^2R$

Decibels and Common EMC Units

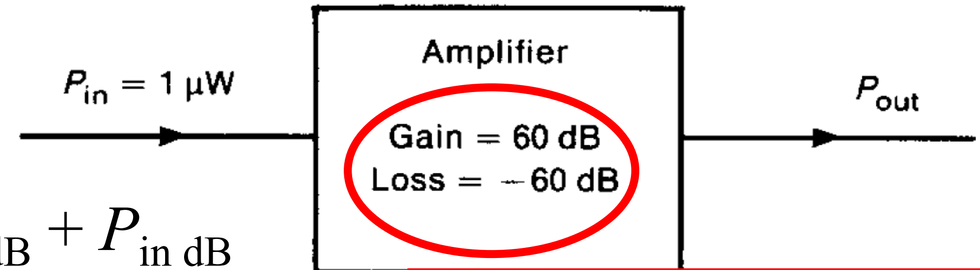
- Power and Voltage (Current) Gains
  - Conversion to Decibels

Ratio	V or I in dB	P in dB
10^6	120	60
10^5	100	50
10^4	80	40
10^3	60	30
10^2	40	20
10	20	10
9	19.08	9.54
8	18.06	9.03
7	16.9	8.45
6	15.56	7.78
5	13.98	6.99
4	12.04	6.02
3	9.54	4.77
2	6.02	3.01
1	0	0
10^{-1}	−20	−10
10^{-2}	−40	−20
10^{-3}	−60	−30

Decibels and Common EMC Units

- Decibel in Computing Amplifier Performance
  - Usage of Power Gain
    - Since the power gain is defined as

$$\text{Gain} = P_{out}/P_{in}$$



    - Thus, we have

$$P_{\text{out dB}} = \text{Gain}_{\text{dB}} + P_{\text{in dB}}$$
$$P_{\text{out dBm}} = \text{Gain}_{\text{dB}} + P_{\text{in dBm}}$$
$$P_{\text{out dB}\mu\text{w}} = \text{Gain}_{\text{dB}} + P_{\text{in dB}\mu\text{w}}$$

Observing that the gain and loss are opposite in sign.

    - When $R_{in}=R_L$, we have

$$v_{\text{out dB}} = \text{Gain}_{\text{dB}} + v_{\text{in dB}}$$
$$i_{\text{out dB}} = \text{Gain}_{\text{dB}} + i_{\text{in dB}}$$

(dBmV, dBμV) and (dBmA, dBμA) also apply

Decibels and Common EMC Units

- Power Loss in Cables
  - Transmission Line Equation
    - For a lossy transmission line, the waves on it are expressed as

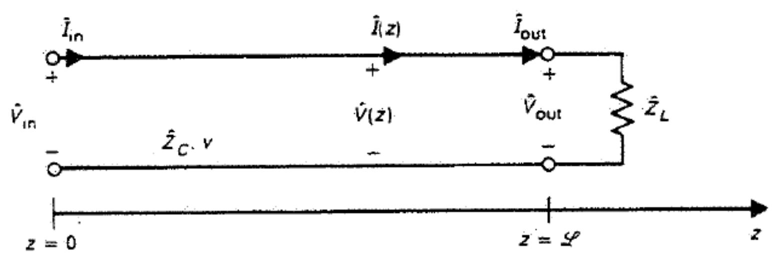
$$\hat{V}(z) = \hat{V}^{+} e^{-\alpha z} e^{-j\beta z} + \hat{V}^{-} e^{\alpha z} e^{j\beta z}$$

$$\hat{I}(z) = \frac{\hat{V}^{+}}{\hat{Z}_C} e^{-\alpha z} e^{-j\beta z} - \frac{\hat{V}^{-}}{\hat{Z}_C} e^{\alpha z} e^{j\beta z}$$

    - When the line is matched, i.e. $Z_L = Z_C$,

$$\hat{V}(z) = \hat{V}^{+} e^{-\alpha z} e^{-j\beta z} = \hat{V}_f(z)$$

$$\hat{I}(z) = \frac{\hat{V}^{+}}{\hat{Z}_C} e^{-\alpha z} e^{-j\beta z} = \frac{\hat{V}_f(z)}{\hat{Z}_C}$$



    - The average power delivered to the right is

$$P_{av}(z) = \frac{1}{2} \mathscr{Re}[\hat{V}(z)\hat{I}^{*}(z)] \longrightarrow P_{media}(z) = \frac{1}{2}\frac{V^{+2}}{Z_C} e^{-2\alpha z} \cos\theta_{Z_C}$$

Decibels and Common EMC Units

- Power Loss in Cables
  - Power Loss
    - The power loss is defined as

$$\frac{P_{\text{media}}(z=0)}{P_{\text{media}}(z=\mathscr{L})} = e^{2\alpha\mathscr{L}}$$

    - which is the cable loss expressing in dB as

$$\begin{aligned}\text{Cable loss}_{\text{dB}} &= 10\log_{10} e^{2\alpha\mathscr{L}} \\ &= 20\alpha\mathscr{L}\log_{10} e \\ &= 8,686\alpha\mathscr{L}\end{aligned}$$

    - Thus, the attenuation constant could be obtained from

$$\alpha = \frac{\text{power loss in dB/length}}{8.686L}$$

    - An important relationship between voltage and power is satisfied when R_L=50Ω

$P_L = v_L^2/R_L$

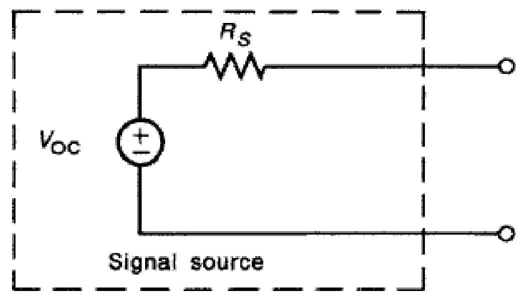
$\downarrow$

$10\log P_L = 10\log(v_L^2/R_L)$ $\longrightarrow$ dBμV (RMS) = 107 + dBm

voltage power

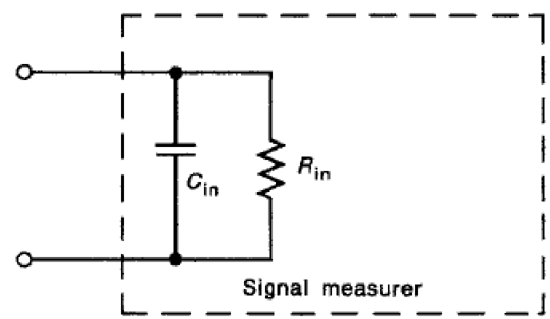
Decibels and Common EMC Units

- Signal Source Specification
  - Signal Source
    - Signal sources can be characterized in terms of a Thevenin equivalent. Virtually all signal sources today have R_S=50 Ω.



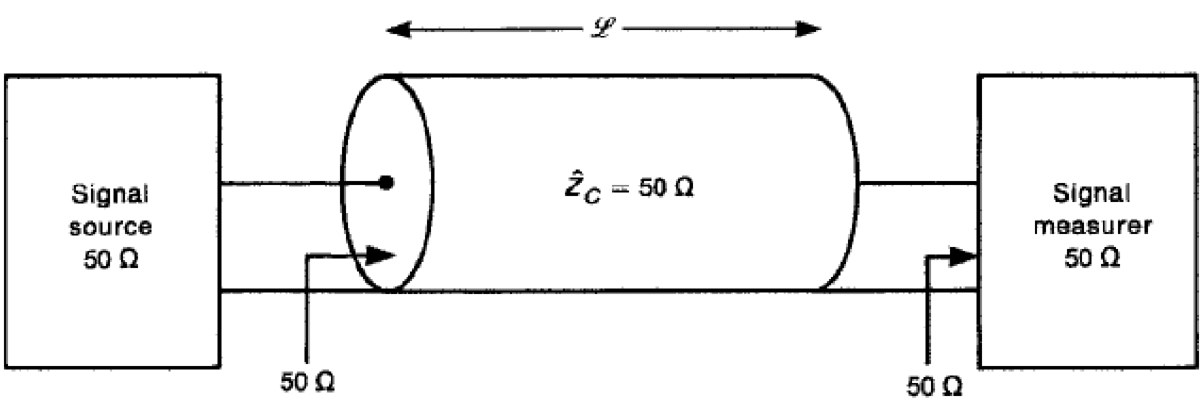
  - Measurement Instrument
    - The vast majority of instruments used to measure signals have an input resistance of 50Ω where C_{in}=0 and R_{in}=50 Ω.

- Typical spectrum analyzer: C_{in}=0 and R_{in}=50 Ω
- Typical Oscilloscope: C_{in}=47 pF and R_{in}=1 MΩ



Decibels and Common EMC Units

- Measurement Setup
  - Typical Measurement System
    - Because the load on this cable equals Z_C, the cable is matched, and the input impedance, at any frequency and for any length of the cable, is Z_{in}=50 Ω=Z_C.
    - If the load does not equals Z_C, the input impedance to the cable as seen by the signal source would vary with frequency and cable length.



Decibels and Common EMC Units

- Measurement Setup
  - Frequency-Independence of Load Impedance
    - It is frequently important to be able to perform swept-frequency measurements in which the frequency of the source is swept over a band.
    - If we could not rely on the output being constant with frequency, this swept measurement would be useless since we would not know the output at a particular frequency! This illustrates why modern EMC test equipment have input and source impedances of pure 50 Ω and are connected by 50-Ω coaxial cables!