UNDERSTANDING AND CONTROLLING COMMON-MODE EMISSIONS IN HIGH-POWER ELECTRONICS

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THE BASIC PROBLEM

- Switching Power Supplies and Variable Speed Motor Drives Produce Large Noise Currents Which are Conducted Out to the Load, as Well as Conducted Back to The Power Source
- These Common-Mode Noise Currents are the Cause of:
  - Low Frequency Conducted Emission, and
  - High Frequency Radiated Emission
- Once One Has an Understanding of the Noise Source and Coupling Mechanism, a Solution Can be Determined
- Power Line Filters in Combination With Proper Load Side Filtering, Grounding, and/or Shielding Will Usually Solve Most Common-Mode Emission Problems.

BASIC PRINCIPLE OF EMC

Return Current to its Source as Locally and Compactly as Possible

Minimize the Loop Area

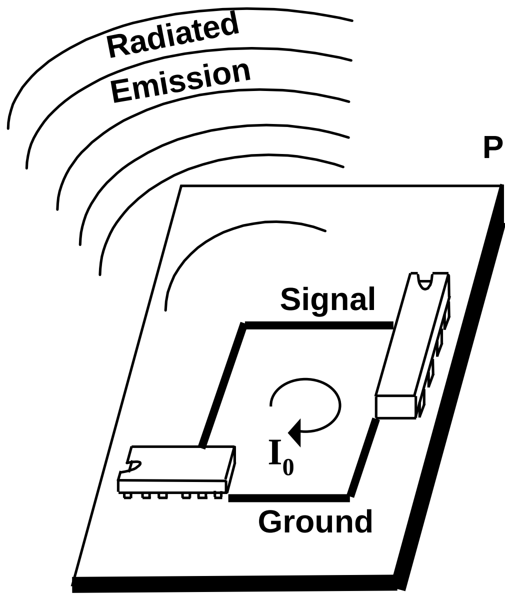
COMMON-MODE & DIFFERENTIAL MODE NOISE

- **Differential-Mode Noise**
  - — Involves the Normal Operation of the Circuit
  - — Currents Flowing Around Loops
  - — Is Documented
    - Schematics
    - PCB Layout
    - Wiring Diagrams
  - — Is Easy to Understand

- **Common-Mode Noise**
  - — Does Not Relate to the Normal Operation of the Circuit
  - — Involves Parasitics
  - — Currents Flow Around Loops Usually Involving Parasitic Capacitance
  - — Is Not Documented
  - — Is More Difficult to Understand
  - — The Noise Source and Current Path Must First be Visualized and Understood Before a Solution Can be Determined

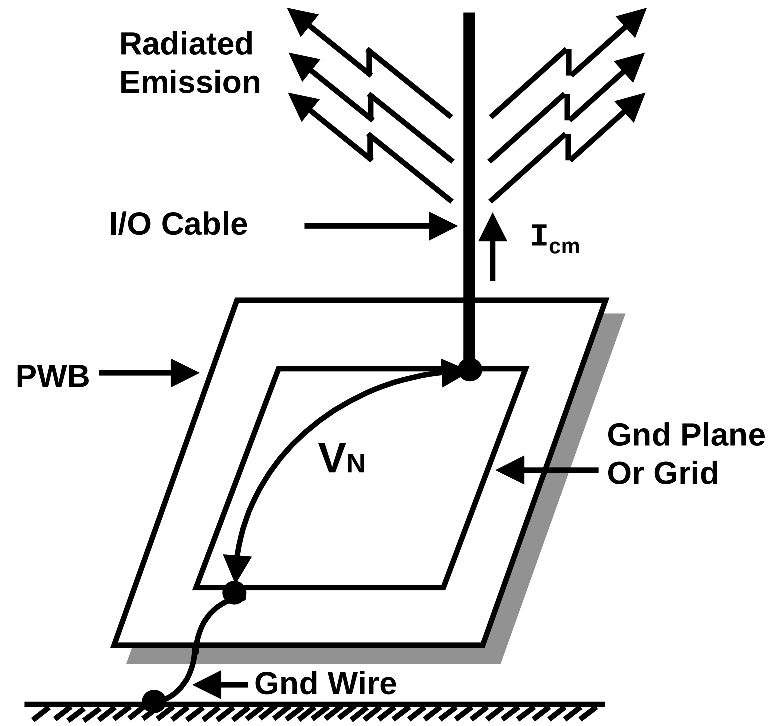
RADIATION MECHANISMS

DIFFERENTIAL-MODE RADIATION



$$E = K_1 f^2 A I_0$$

COMMON-MODE RADIATION

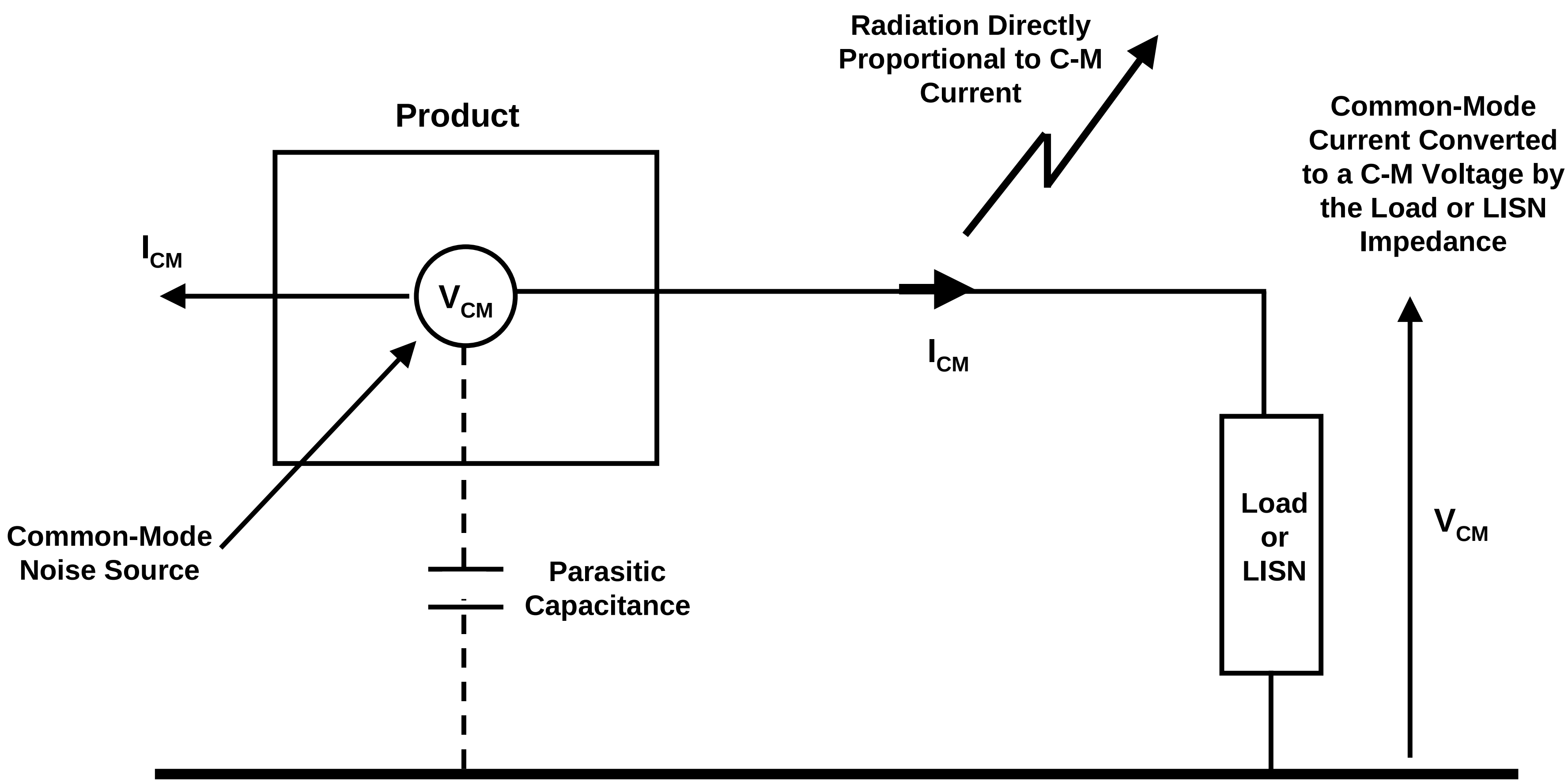


$$E = K_2 f L I_{cm}$$

BASIC ANTENNA TYPES

Antenna Type	Radiation Mechanism	Electromagnetic Field
Loop	Differential-Mode	Magnetic Field
Dipole	Common-Mode	Electric Field

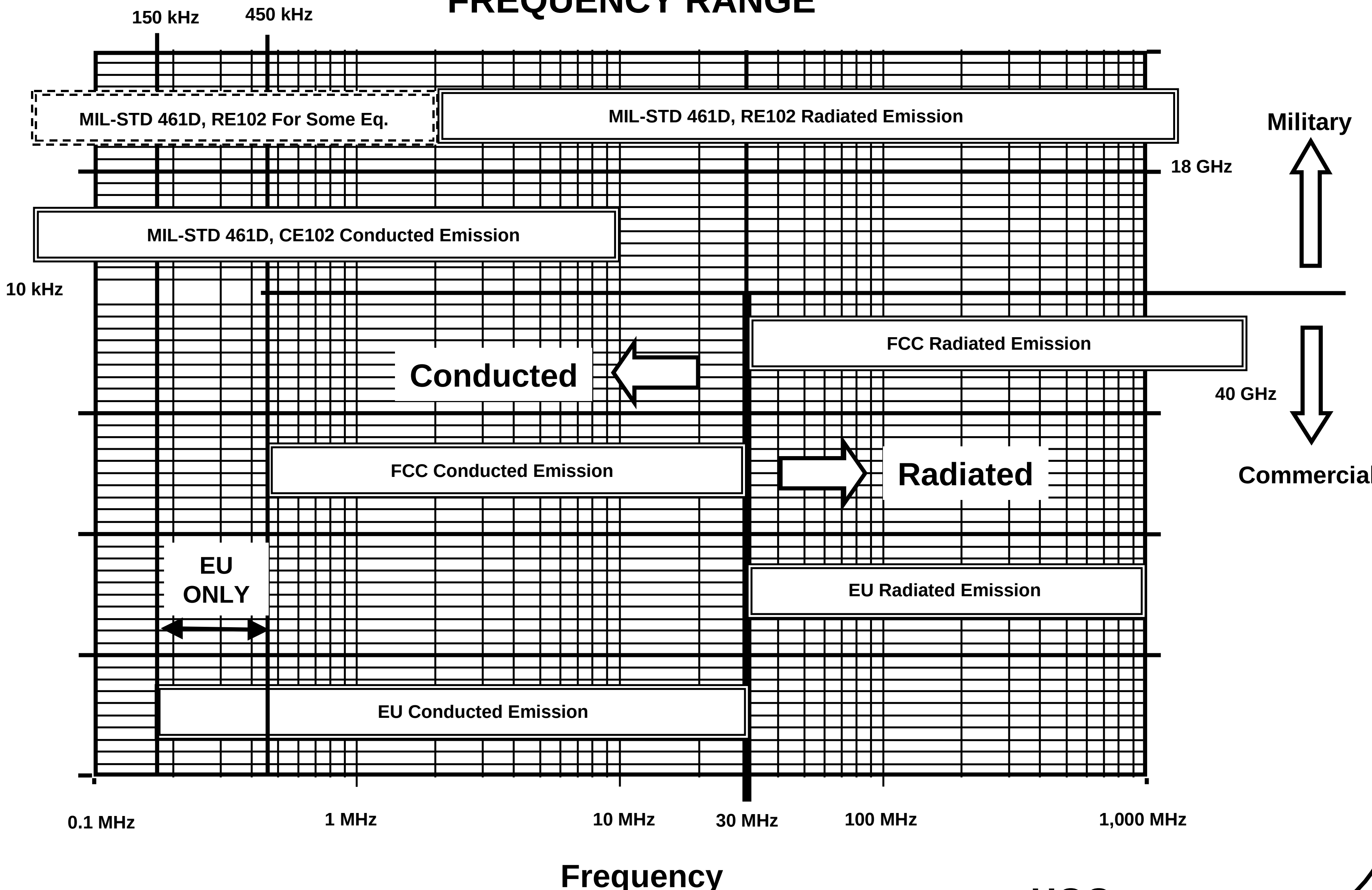
RADIATED VERSUS CONDUCTED C-M EMISSION



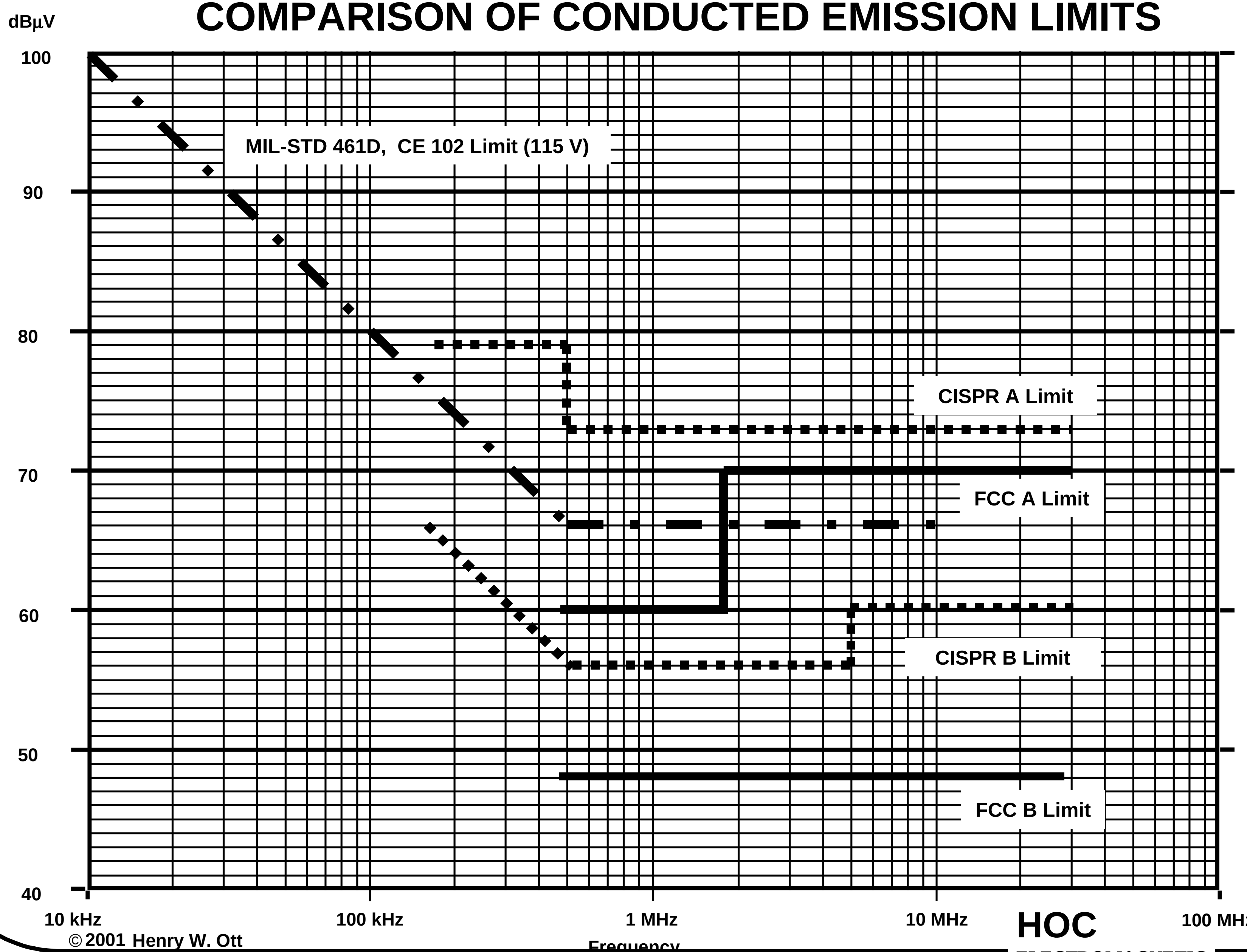
EMC REGULATIONS PERTAINING TO C-M EMISSIONS

- North America (FCC/Industry Canada)
- European Union (EU)
- Military (MIL-STD)

FREQUENCY RANGE



COMPARISON OF CONDUCTED EMISSION LIMITS



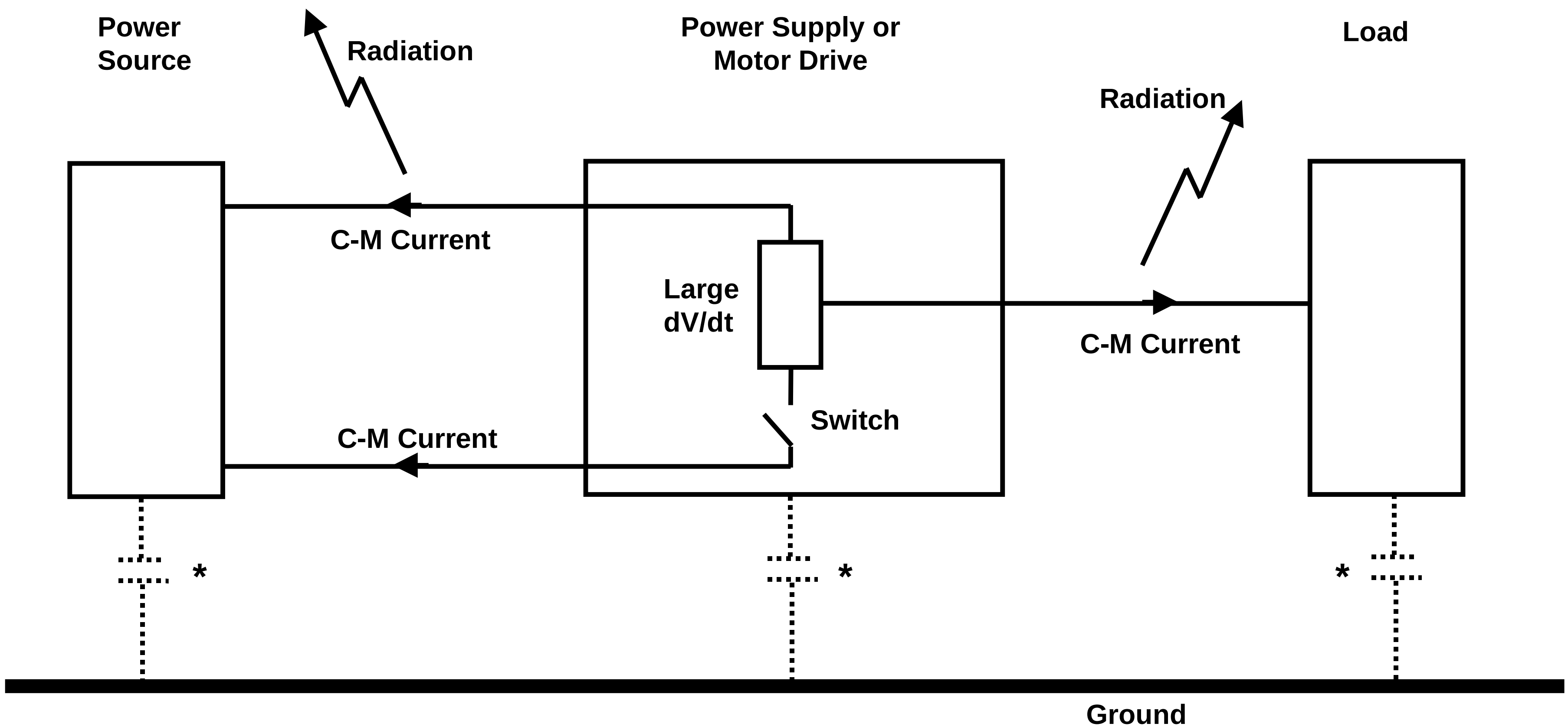
HOC
ELECTROMAGNETIC
COMPATIBILITY

HOW MUCH C-M CURRENT IS A PROBLEM
(Based on FCC Requirements)

Frequency	Class A	Class B
<1.7 MHz *	40 uA	10 uA
1.7 - 30 MHz*	120 uA	10 uA
30MHz**	24 uA	8 uA
50 MHz**	15 uA	5uA
100 MHz**	11uA	3.5 uA

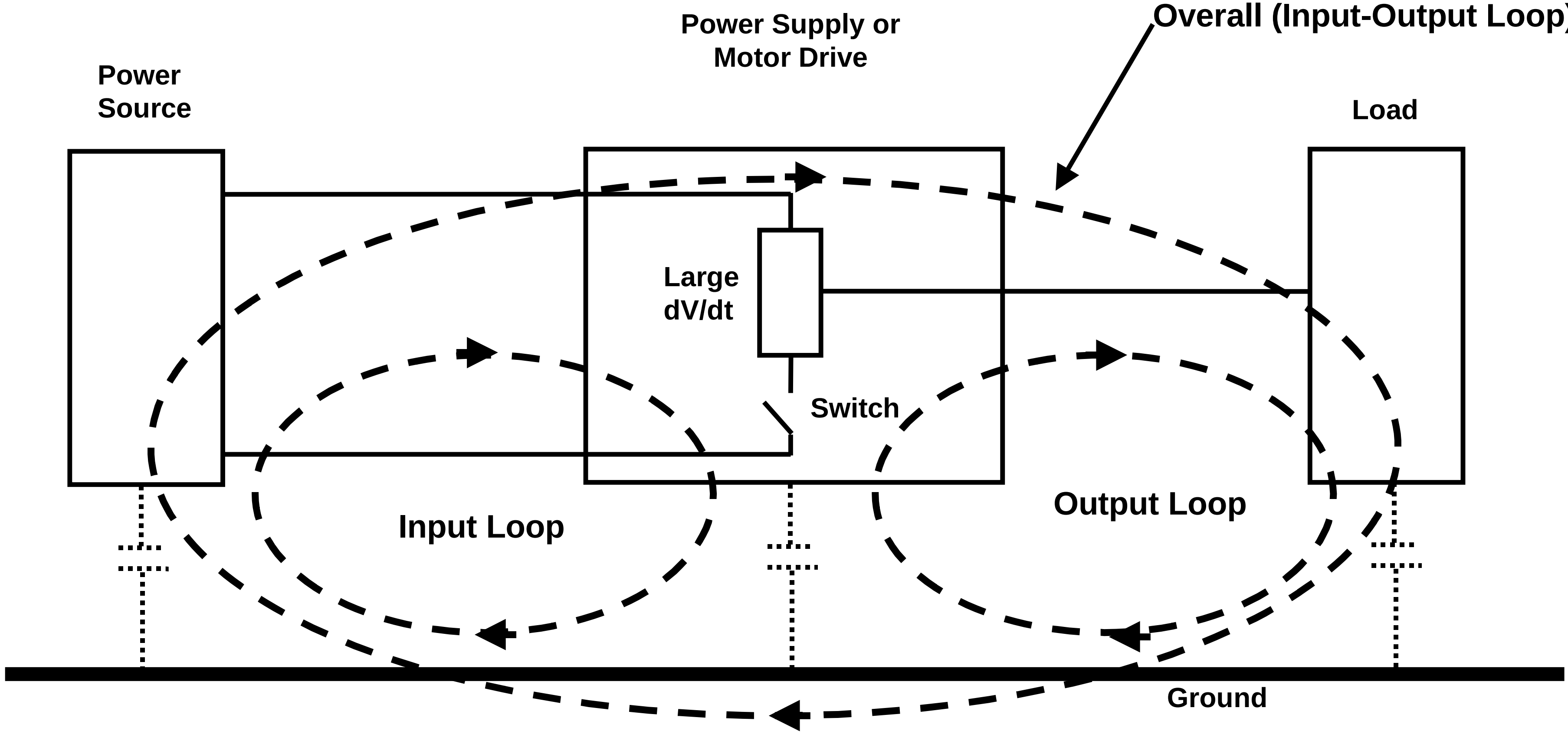
* Based on Conducted Emission Limits
** Based on Radiated Emission Limits

THE BASIC C-M PROBLEM



* Any of the parasitic capacitance's could be a metallic connection to ground

C-M CURRENT LOOPS



There Are Three Possible Loops to be Concerned With

THE INVISIBLE SCHEMATIC

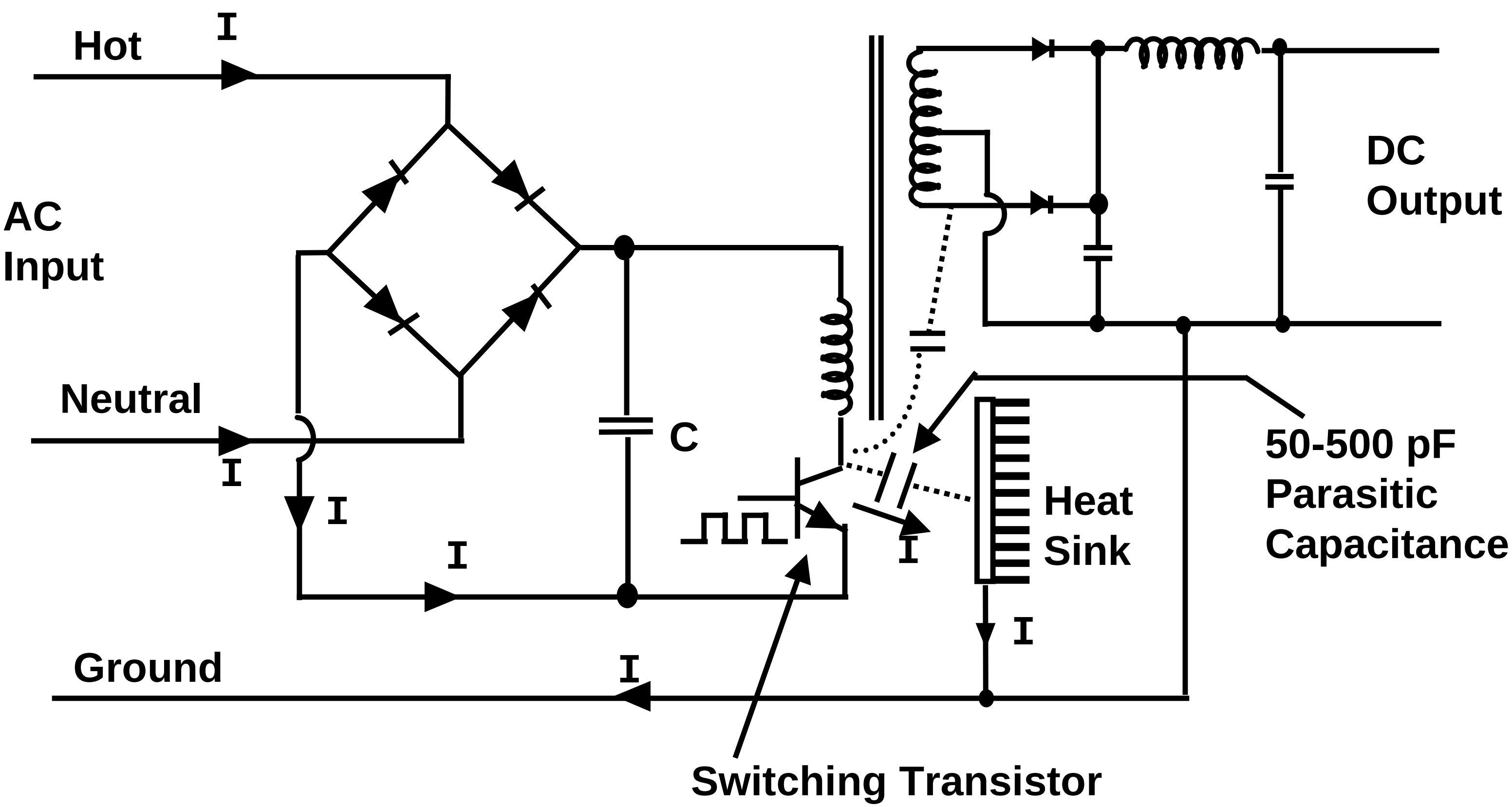
- Consists of:
  - — the dV/dt Generator, and
  - — the Parasitic Capacitance
- You Should be Able to Find and Visualize These Components
- Once the Invisible Schematic Components are Identified, the Required Control Techniques Become Fairly Straightforward and Obvious. They are not “Black Magic.”

C-M EMISSION CONTROL TECHNIQUES

- Find a Way to:
  - — Reduce the Magnitude of the Source (dV/dt)
  - — Reduce the Parasitic Capacitance
  - — Reduce the C-M Current (e.g. Filtering)
  - — Return the C-M Current Through a Small Loop That Does Not Involve the External Ground Path (Small Loop Area)
- Usually The Closer You Can Get The Control to the Noise Source (the dV/dt Generator*) the More Effective the Technique

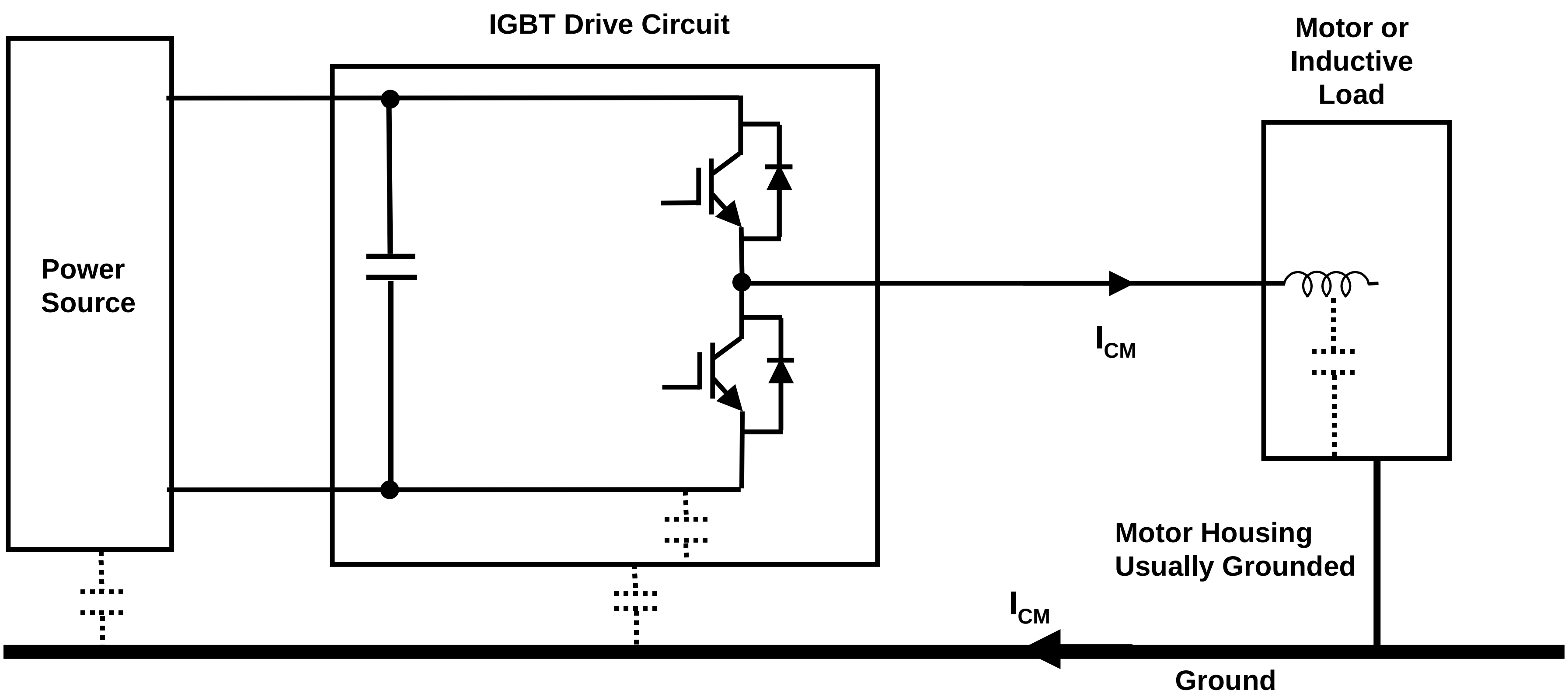
* Usually the Switching Transistors

SWITCHING POWER SUPPLY CONDUCTED EMISSION, COMMON-MODE



I = C-M Noise Current

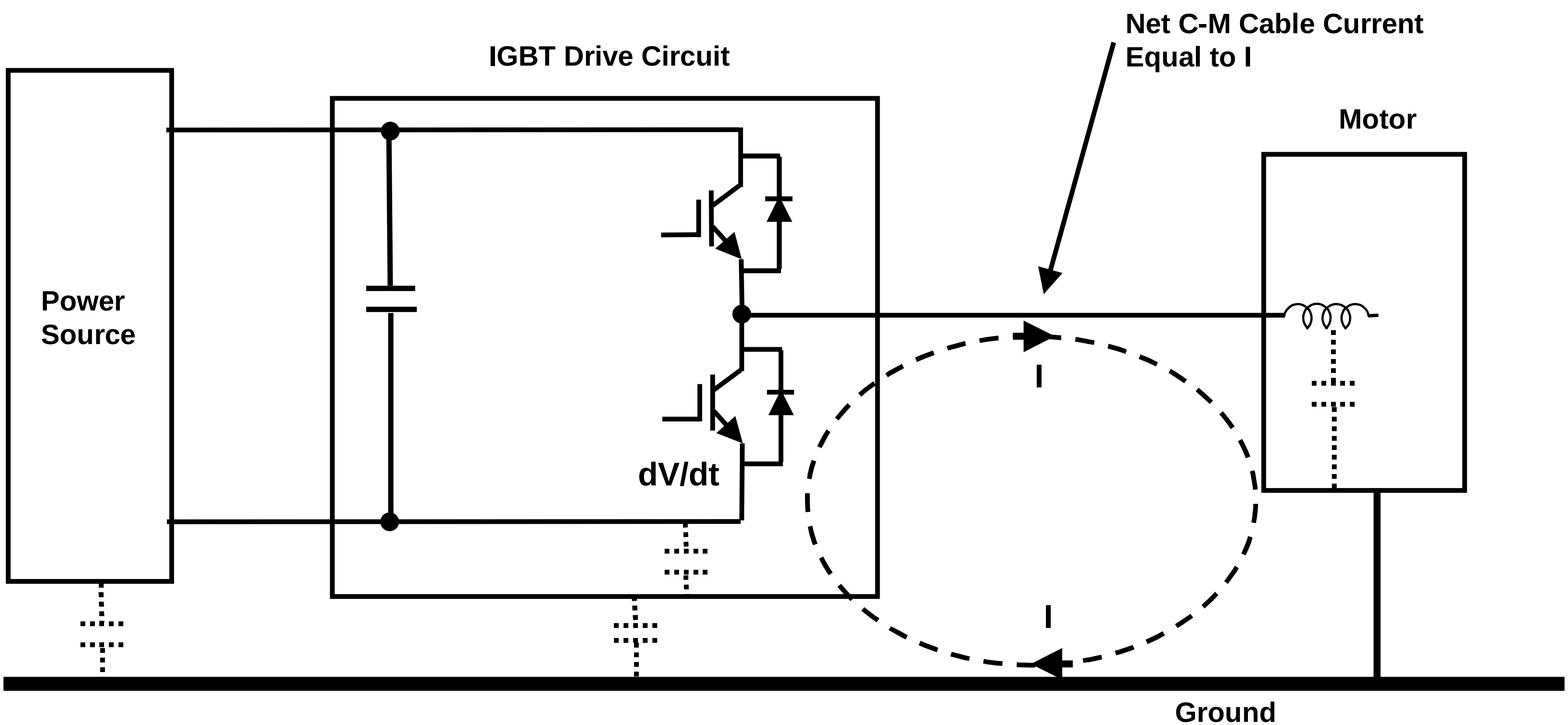
BASIC IGBT MOTOR DRIVE



BASIC SOLUTIONS TO THE C-M PROBLEM

- Minimize the dV/dt
- Reduce the Parasitic Capacitance
- Use Filtering
  - — To Reduce the C-M Current on the Cable
- Use Grounding
  - — To Return the C-M Current
- Use Shielding
  - — To Return the C-M Current
  - — To Reduce the Parasitic Capacitance

BASIC IGBT MOTOR DRIVE



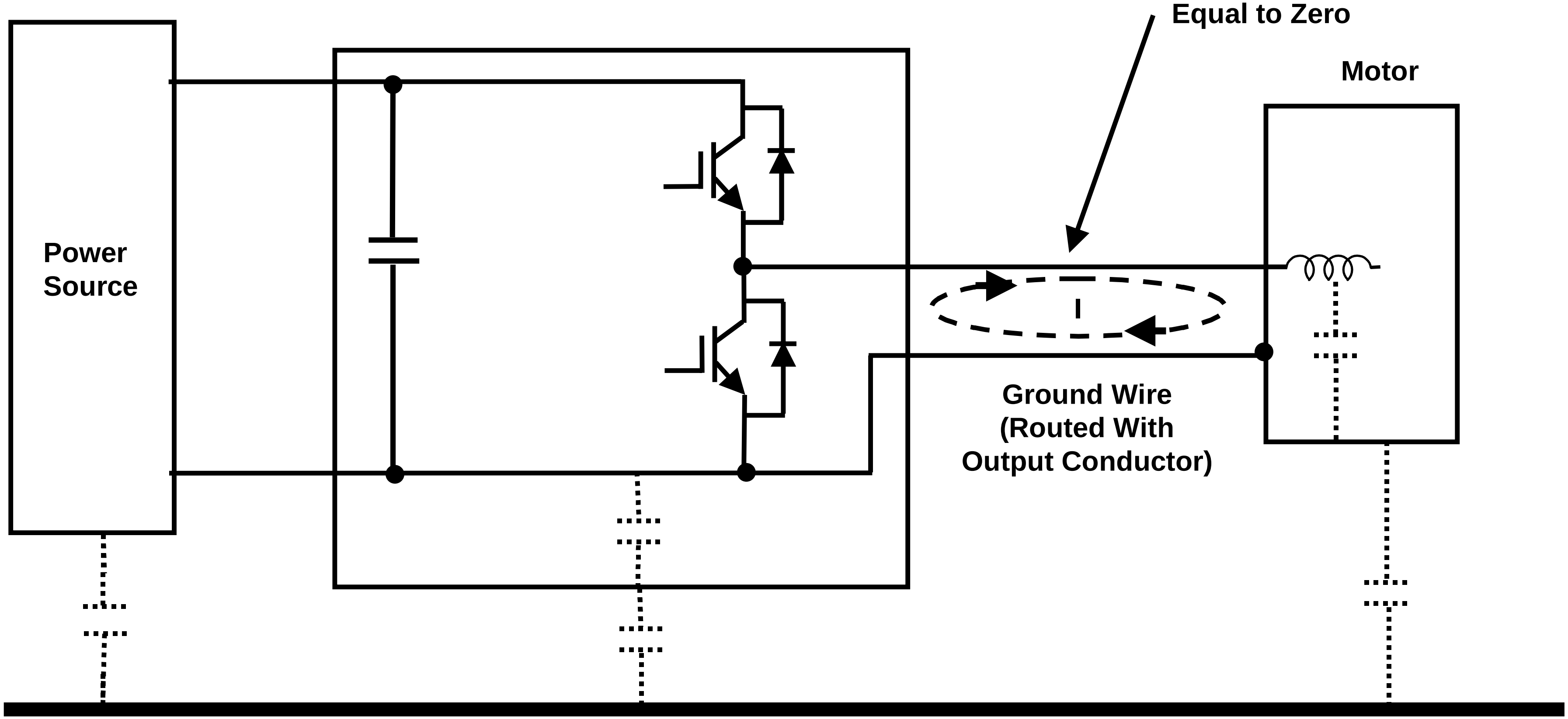
THE BASIC IGBT MOTOR DRIVE PROBLEM (LOAD SIDE C-M CURRENT)

- The IGBT Switches are the C- M Voltage Source
- This Causes a Large Current (dI/dt) to Flow On the Output Leads to the Motor
- The Low Frequency Current Goes Through the Motor Windings as Intended
- The High Frequency Current, However, Capacitively Couples to The Motor Housing (Which is Usually Grounded)
- The Return Current Path Can Vary But Usually Flows Through the External Ground
  - May Capacitively Couple Back to the IGBT Drive (As Shown in the Previous Slide)
  - Or in Some Cases May Flow All the Way Back to the Power Source and From There Back to the Switches
- In All Cases, However, The Problem Arises Because of the Capacitance Between the Motor Windings and the Housing

POSSIBLE SOLUTIONS

- Power Input Side of the Switch
  - Use a Power Line Filter
- Output (Load) Side of Switch
  - Use Grounding or Shielding
    - To Return C-M Current Without Using the External Ground Path
  - Use Filtering
    - To Return the C-M Current Locally to the Switch
  - Reduce the dV/dt or the Motor Capacitance (Not Usually Practical)
- Remember the Switch is the Source of the C-M Voltage and the Motor Capacitance Provides the C-M Current Return Path

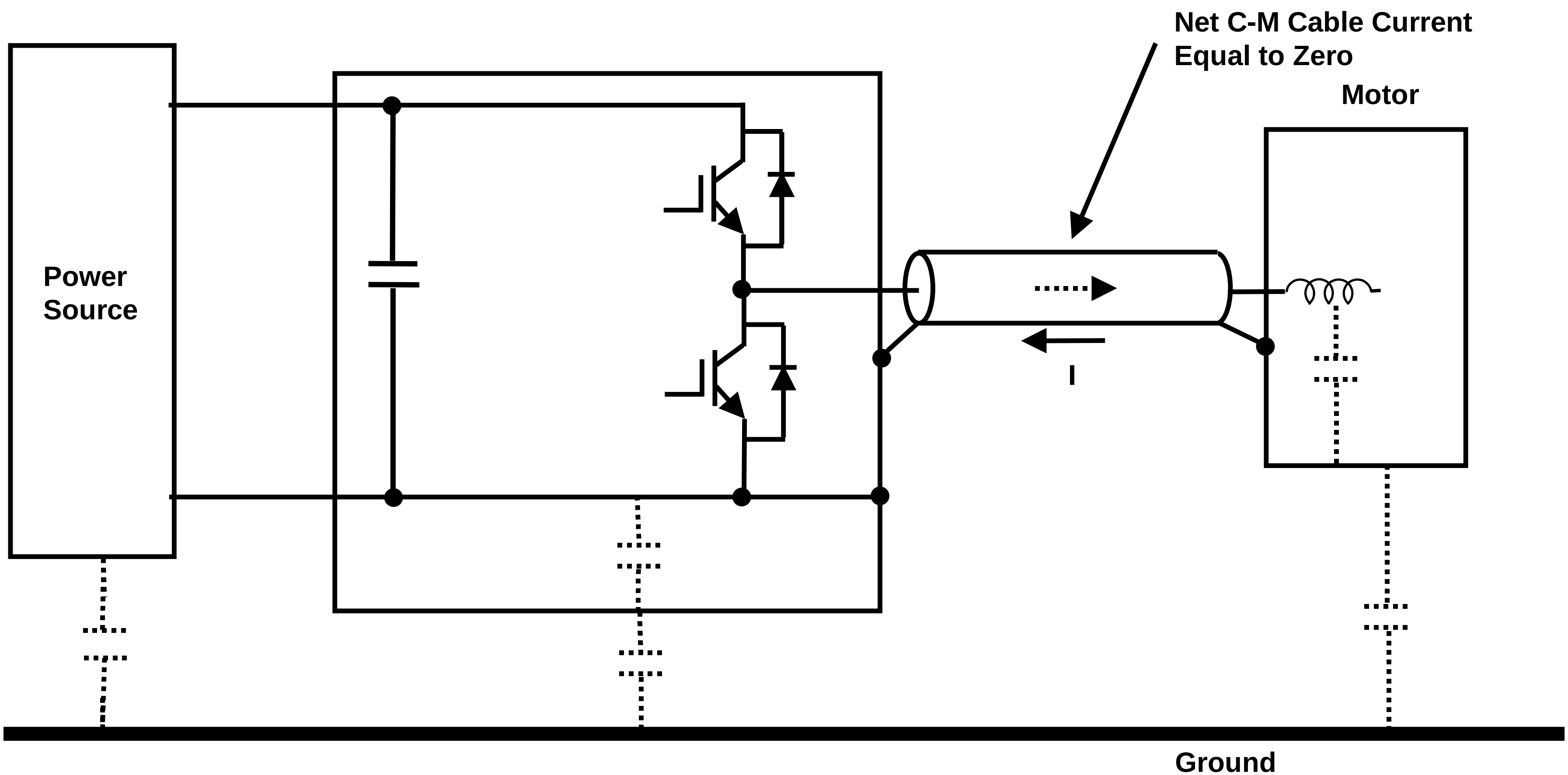
GROUND WIRE FROM MOTOR HOUSING TO SWITCH COMMON



This is the <u>Ideal Solution</u> But May Be Difficult to Implement
Either the Motor Housing Must be Floating (as shown), or the Switch Common Must be Connected to Ground

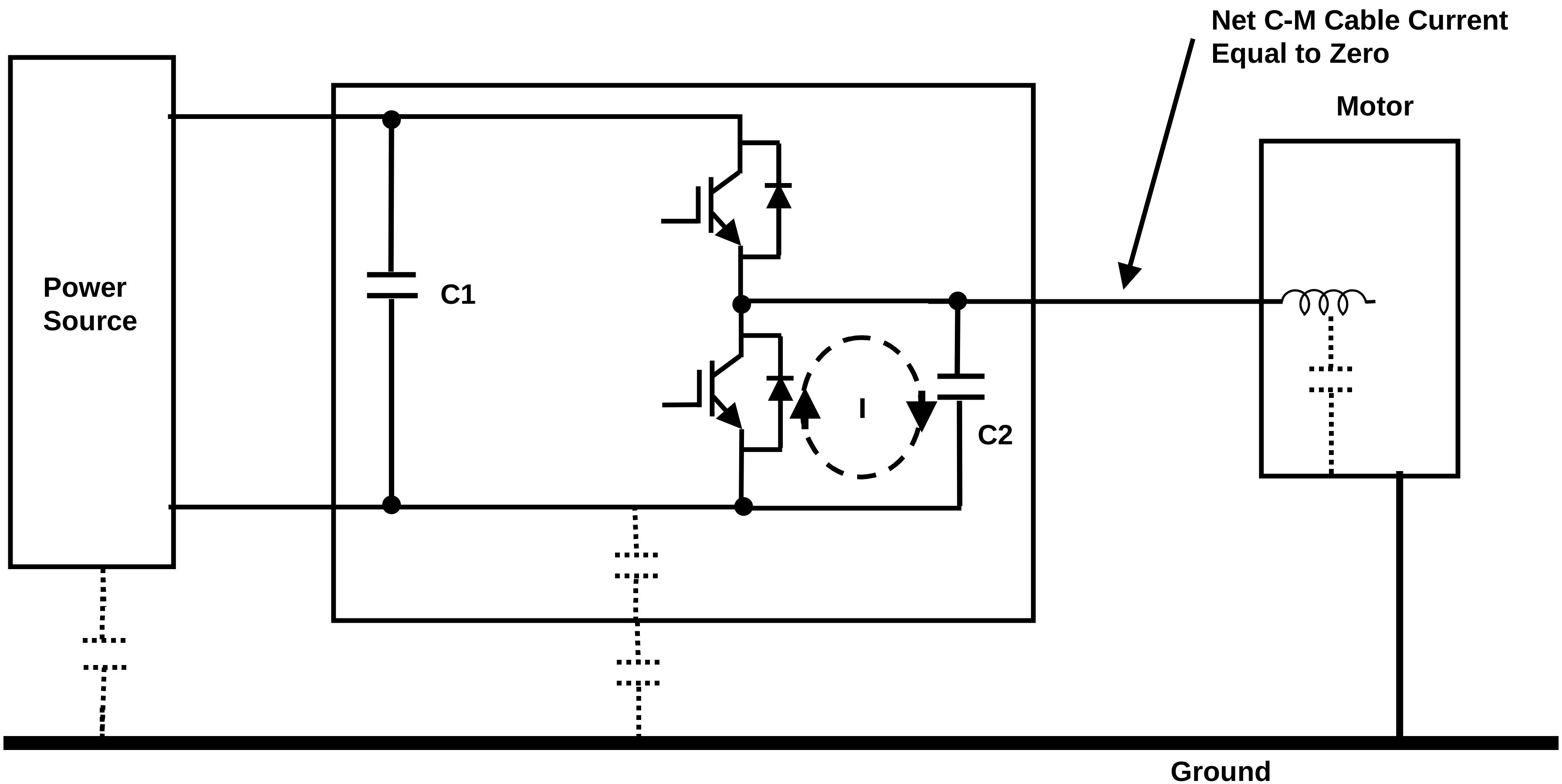
Alternative Approach: Add a Capacitor in Series With the Ground Wire to Provide an AC Connection Only
Capacitor Value Limited by Leakage Current Requirements. Therefore, Not Very Effective at Low Frequencies

SHIELDED CABLE SOLUTION



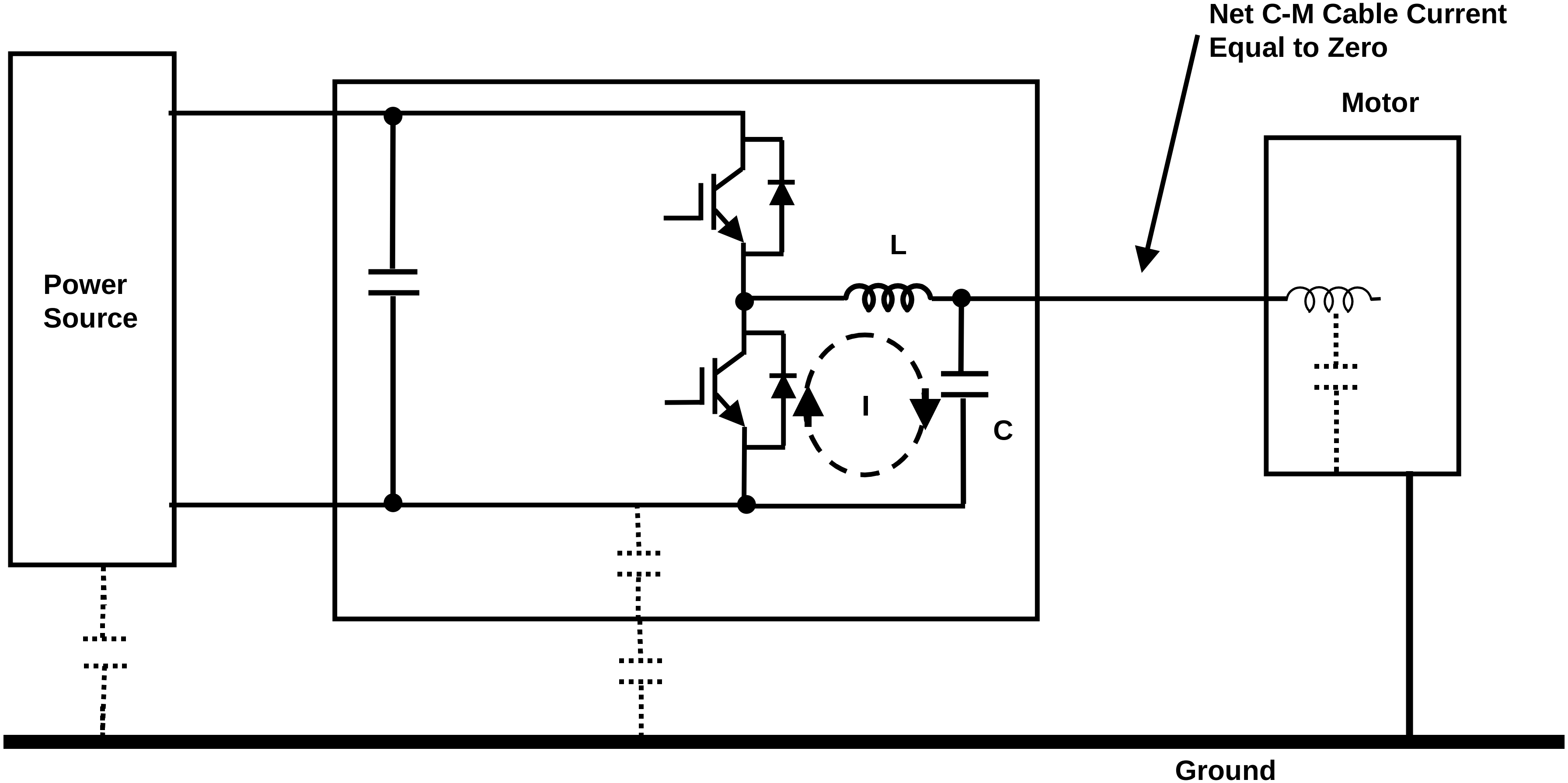
Similar to the Ground Wire Described Previously, But More Effective For Radiated Emission
Shield Must Be Connected to Motor Housing on One End and to the Switch Common on the Other End
Shield May Be Terminated With a Capacitor on One End as a Compromise

CAPACITOR FILTER SOLUTION



Often Tried, However, it is a Good Way to Destroy the IGBT's
You Are Dumping the Contents of a Large Capacitor (C1) Into a Smaller Capacitor (C2)
Through a Low Impedance Switch With No Current Limiting

L - C FILTER SOLUTION

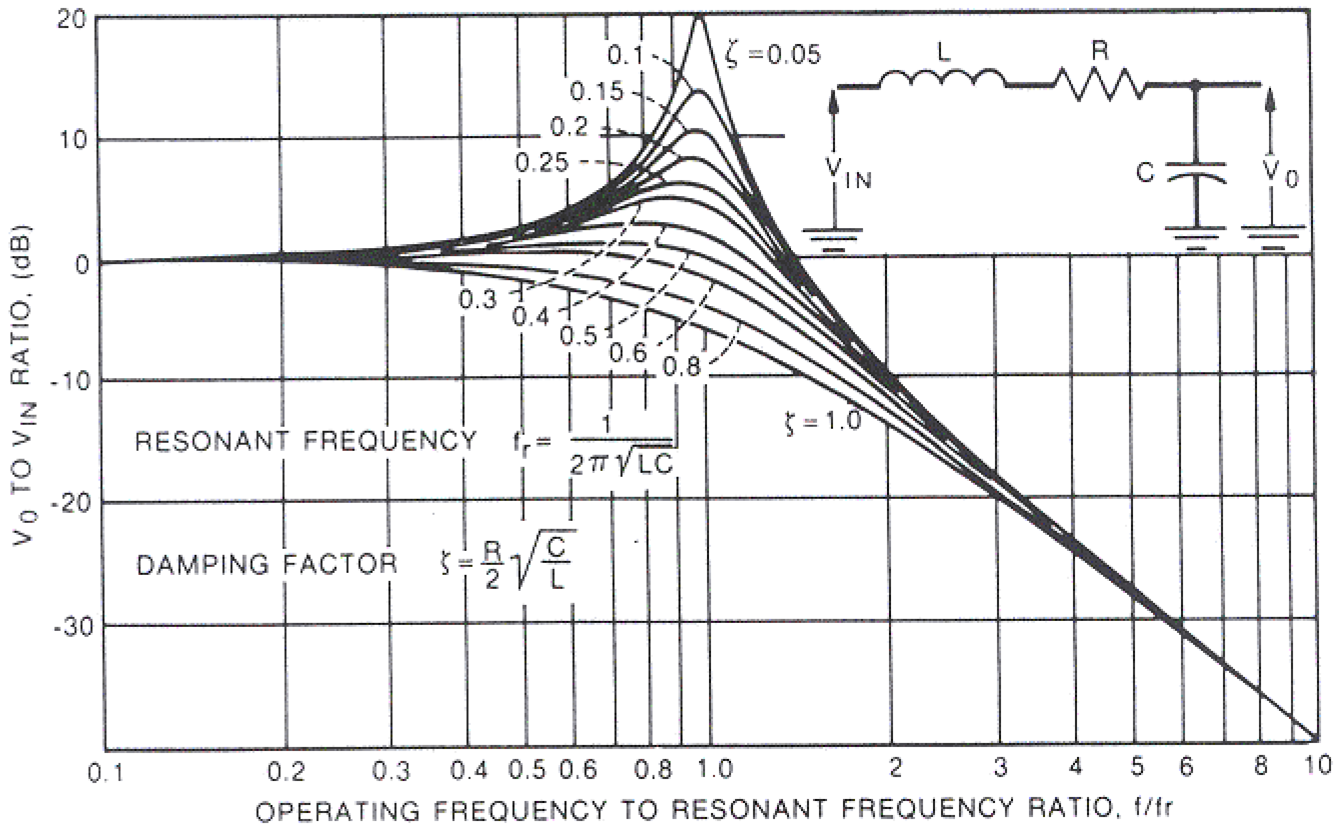


Often The Most Practical Solution, However, Beware of the Resonant Frequency of the Filter - Noise Will be Greater at this Frequency

Inductive Kick of the Inductor Must be Snubbed, IGBT Diodes Will Normally Do This,

You Could Also Use A C-M Choke in Place of the Inductor

DAMPING FACTOR & FILTER RESONANCE



From: Ott, H. W., Noise Reduction Techniques in Electronic Systems, Second Edition, John Wiley, 1988

TYPICAL FILTER COMPONENT VALUES
(L - C FILTER)

Frequency	Capacitor	Inductor	Resonant Freq.
150 kHz	1 uF	100 uH	16 kHz
450 kHz	0.35 uF	35 uH	45 kHz
1 MHz	0.16 uF	16 uH	100 kHz
5 MHz	0.03 uF	3.2 uH	513 kHz
10 MHz	0.015 uF	1.6 uH	1 MHz
20 MHz	8000 pF	0.8 uH	2 MHz
30 MHz	5000 pF	0.5 uH	3 MHz

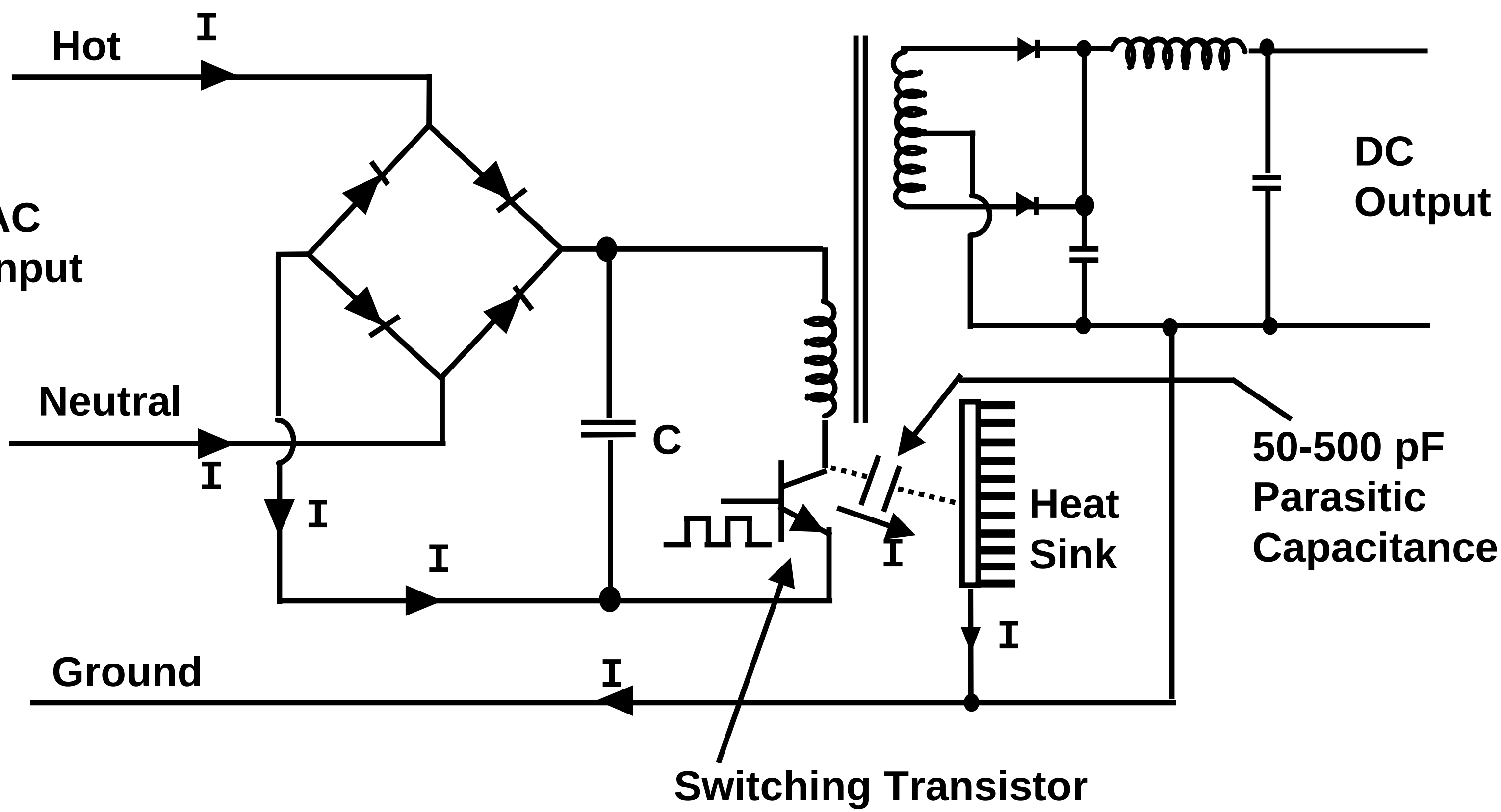
SWITCHING POWER SUPPLY NOISE SOURCES AND COUPLING PATHS

- The Most Common Noise Source is the Switching Transistor (Noise Will Be at Harmonics of the Switching Frequency, Normally Decreasing With Frequency -- Resonances May Cause “Pop-Ups”)
- Second is the Bridge Rectifier Noise (Noise Will Occur at Multiples of 120 Hz and is Differential-Mode)
- Third is Parasitic Oscillation (Usually Occurs at High Frequency and is Not Related to The Switching Frequency or 120 Hz)
- Fourth The Interactions Between the Power Supply & the Power Line Filter (The Power Supply Has a Negative Input Impedance at Power Line Frequencies and Can Oscillate if Terminated Improperly)
- Lastly, High Q Resonances & Other Miscellaneous Sources
- Parasitic Capacitance Provides the C-M Coupling Path
  - Switching Transistor to Heat Sink Capacitance
  - Primary to Secondary of Transformer Capacitance
  - Reduce These Capacitances as Much as Possible

POWER SUPPLY INPUT IMPEDANCE

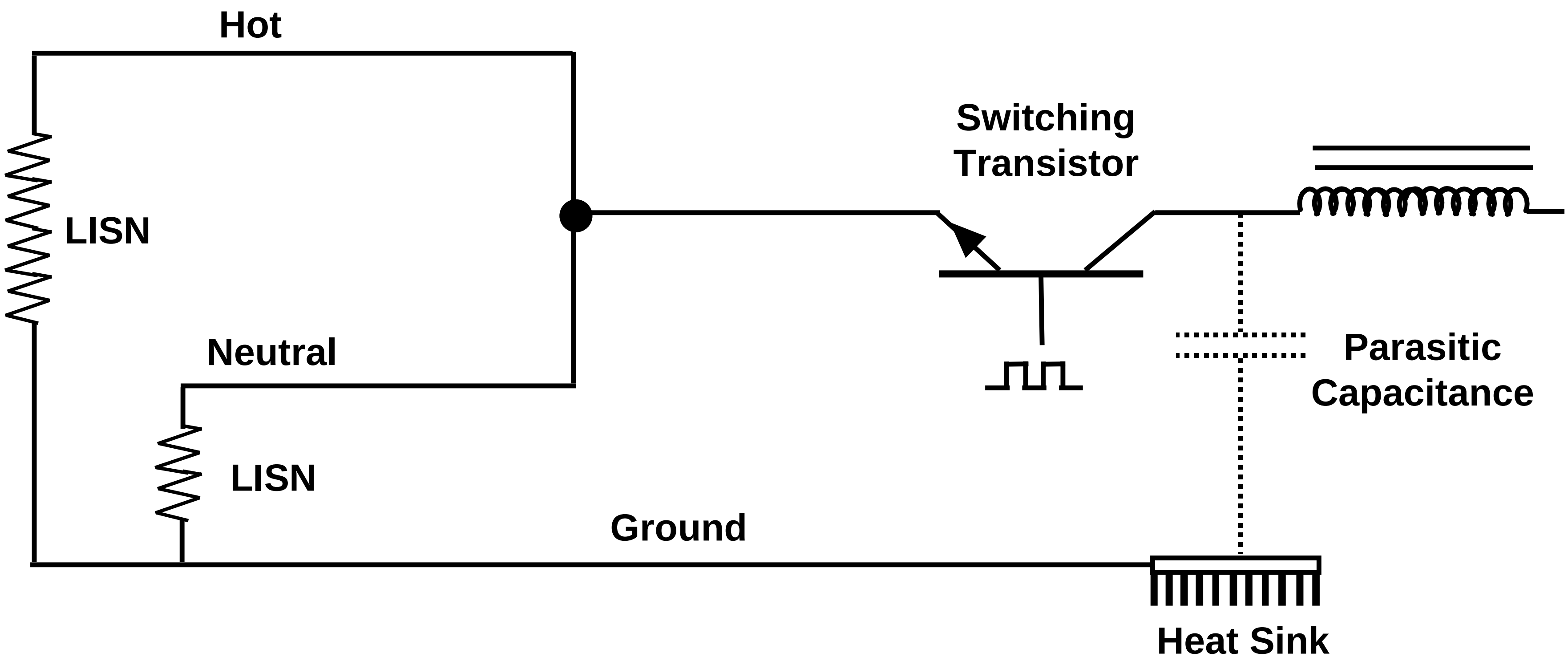
- The Function of a Regulated Power Supply is to Keep the Output Voltage Constant
- If the Output Voltage is Constant, We Can Assume That the Output Current and Output Power Are Also Constant (Assuming a Fixed Load Impedance)
- If the Output Power is Constant, the Input Power Must Also be Constant
- Hence, the Input V x I Product Must be Constant
- If the Input Voltage Decreases, the Input Current Must Increase in Order to Maintain a Constant V x I Product
- Therefore, the Power Supply Has a <u>Negative Input Impedance</u> (The Input Impedance is Actually the Negative Reflected Load Impedance)
- And the Power Supply Can Become Unstable and Oscillate When The Power Line Filter is Added If the Power Line Filter Output Impedance is Not Low Enough

SWITCHING POWER SUPPLY CONDUCTED EMISSION, COMMON-MODE



I = C-M Noise Current

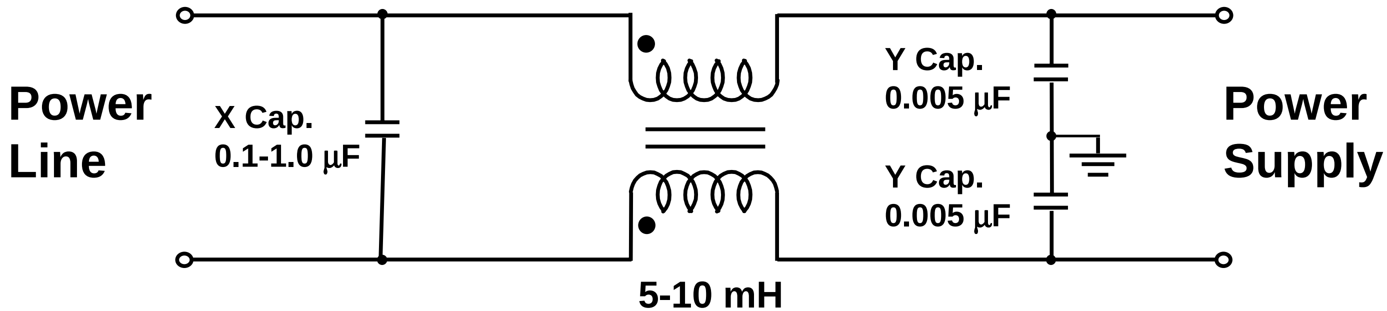
COMMON MODE EQUIVALENT CIRCUIT OF SWITCHING POWER SUPPLY



THE SWITCHING POWER SUPPLY PROBLEM

- **Operating Voltage Level Within Power Supply = 150 V.**
- **Maximum Conducted Emission (Class B) = 250 uV.**
- **250 uV / 150 V = 1.67 x 10^{-6} = -116 dB**
- **The Allowable Conducted Emission Level is <u>One Millionth</u> of the Operating Level**
- **Required Suppression = 120 dB**

TYPICAL POWER LINE FILTER

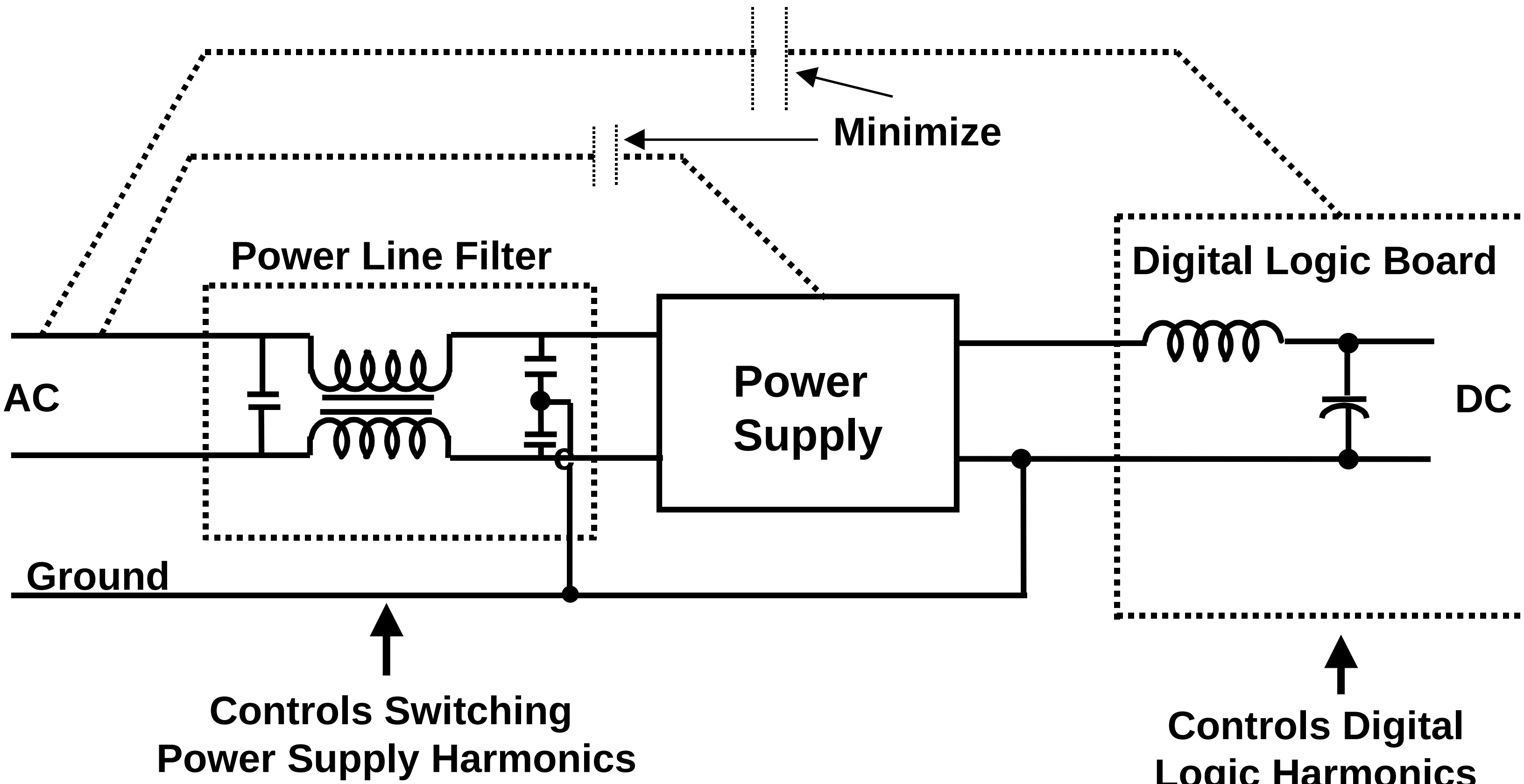


Note:
X Cap. Affects Differential-Mode
Y Cap. Affects Common-Mode, The Series Combination Affects Differential-Mode
Choke Affects Common-Mode, Leakage Inductance Affects Differential-Mode

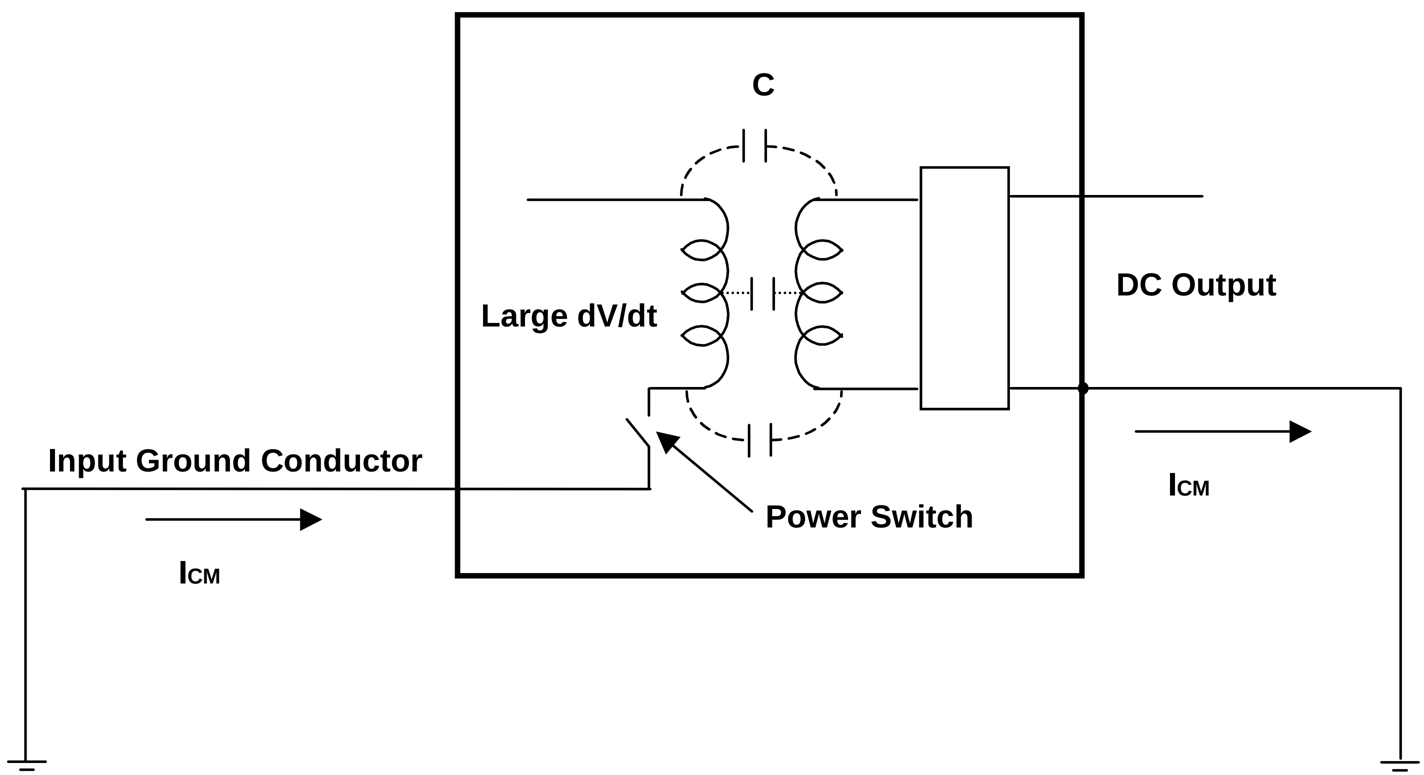
AC POWER LINE FILTERS

The Performance Of An AC Power Line Filter Is As Much A Function Of How And Where the Filter Is Mounted, And How The Leads Are Run To It, As It Is Of The Electrical Design Of The Filter.

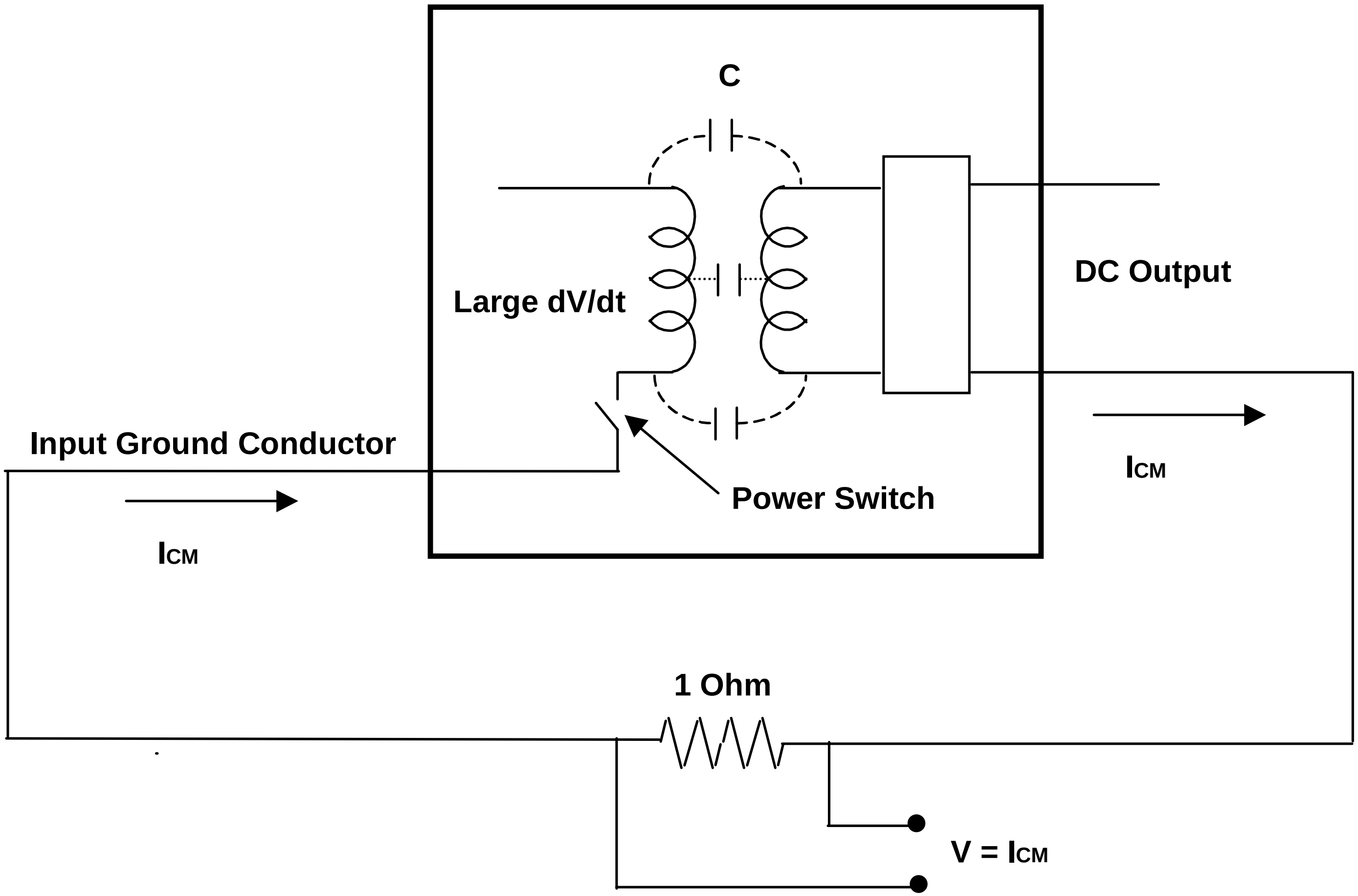
MINIMIZE PARASITICS



GENERATING COMMON-MODE NOISE BETWEEN THE INPUT & OUTPUT OF A SWITCHING POWER SUPPLY



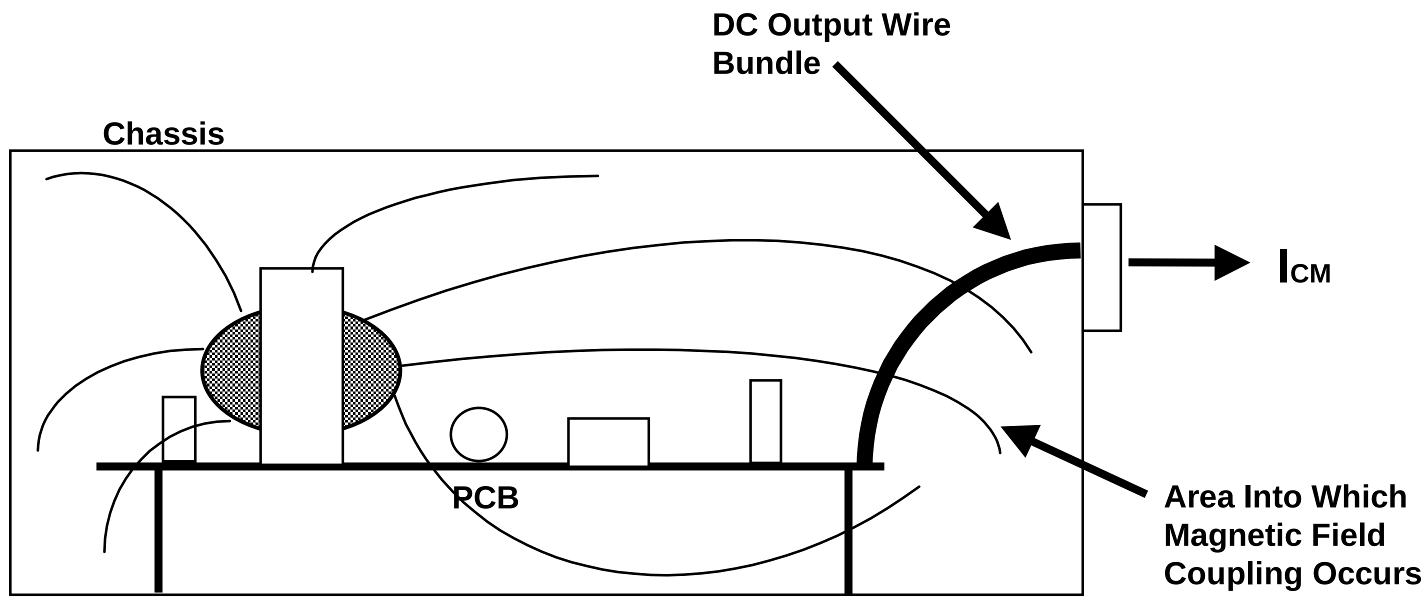
MEASURING THE COMMON-MODE CURRENT BETWEEN INPUT & OUTPUT A SWITCHING POWER SUPPLY



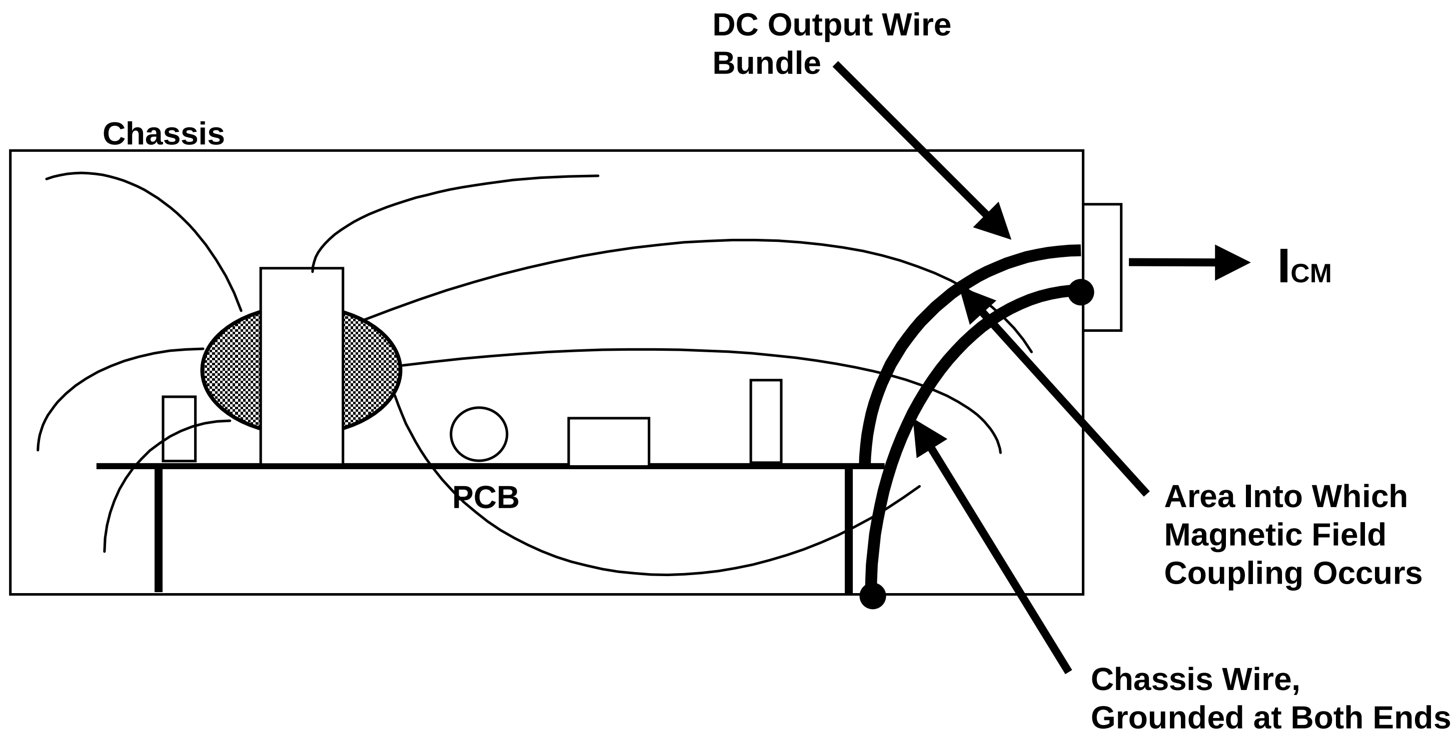
DEALING WITH COMON-MODE NOISE BETWEEN INPUT & OUTPUT OF A SWITCHING POWER SUPPLY

- **Using an Isolated Converter in an Application Where the Input and Output Grounds are Tied Together at a Remote Point Can Often Cause a Problem**
- **Keep the Input and Output Circuits Isolated**
- **Connect Input and Output Grounds Together Internally With a Heavy Strap as Close to the Switching Element as Possible**
- **Add a Common-Mode Choke (Inductor, Ferrite, etc.) to the Input Circuit**
- **Reduce Transformer Inter-winding Capacitance**
- **Add a Faraday Shield to the Transformer**
- **Add a Choke to the DC Output Ground Lead**

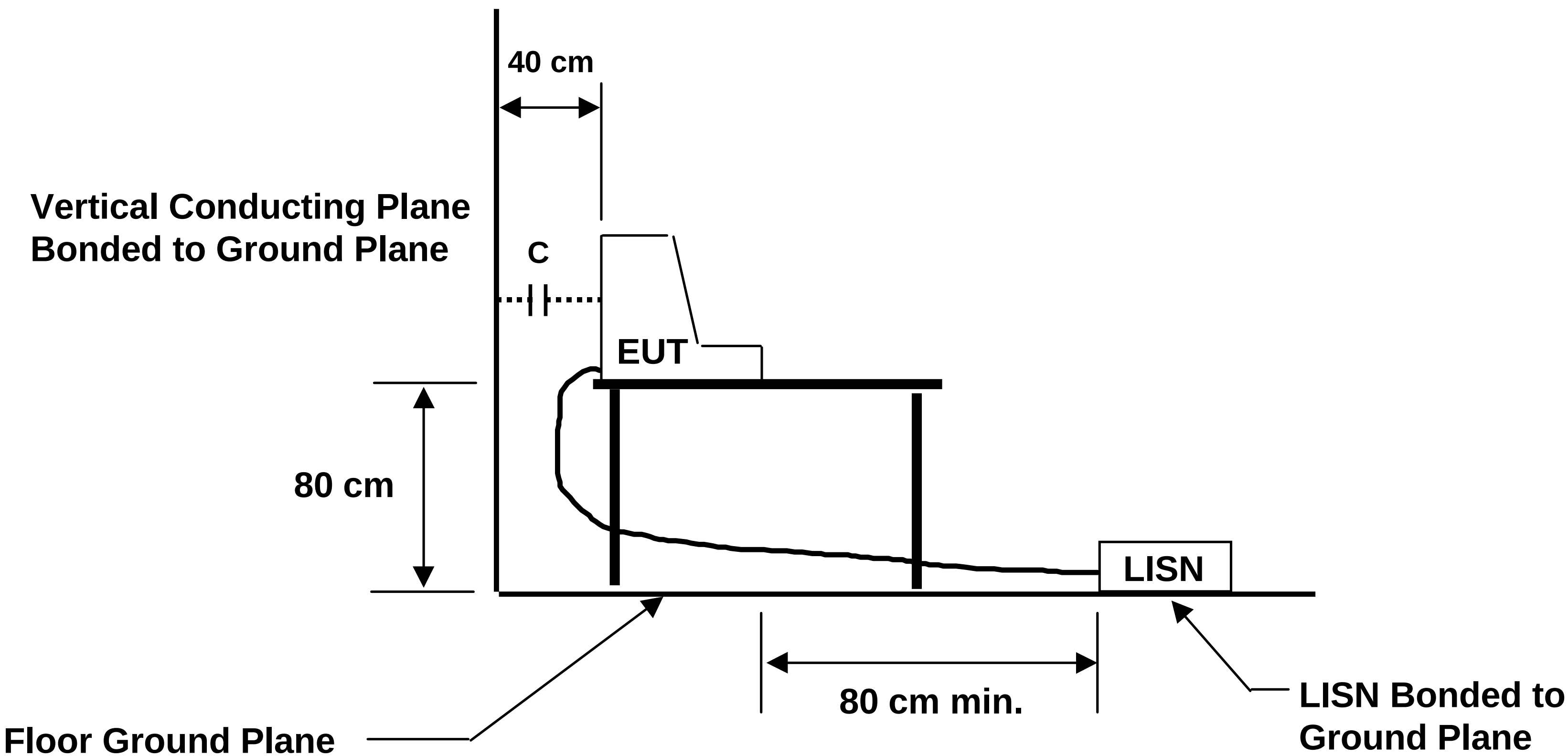
MAGNETIC FIELD COUPLING TO OUTPUT WIRES



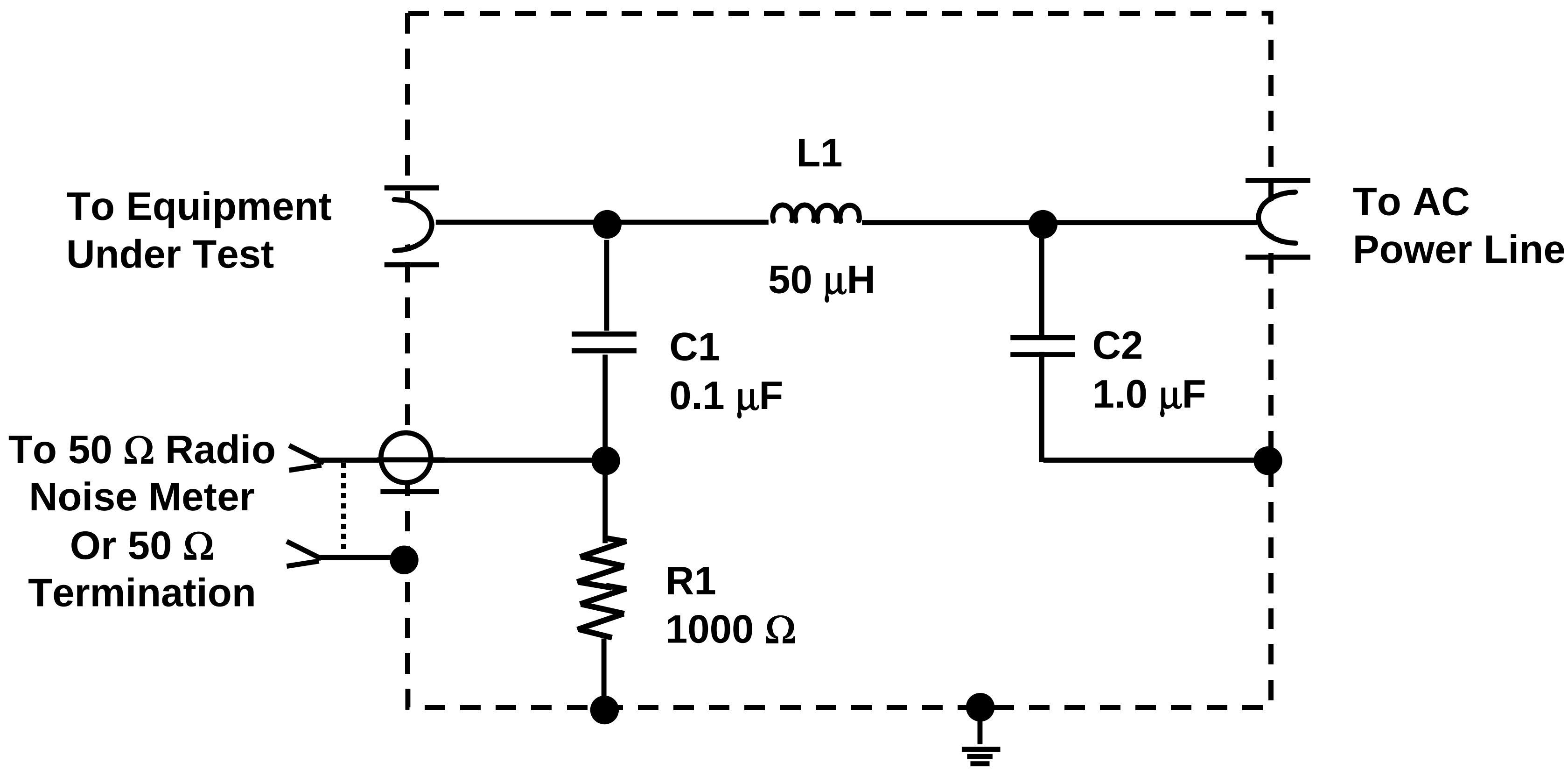
THE CHASSIS WIRE CONCEPT



CONDUCTED EMISSION TEST SET-UP



50 μH LISN SPECIFIED BY THE FCC



TROUBLESHOOTING CONDUCTED EMISSION

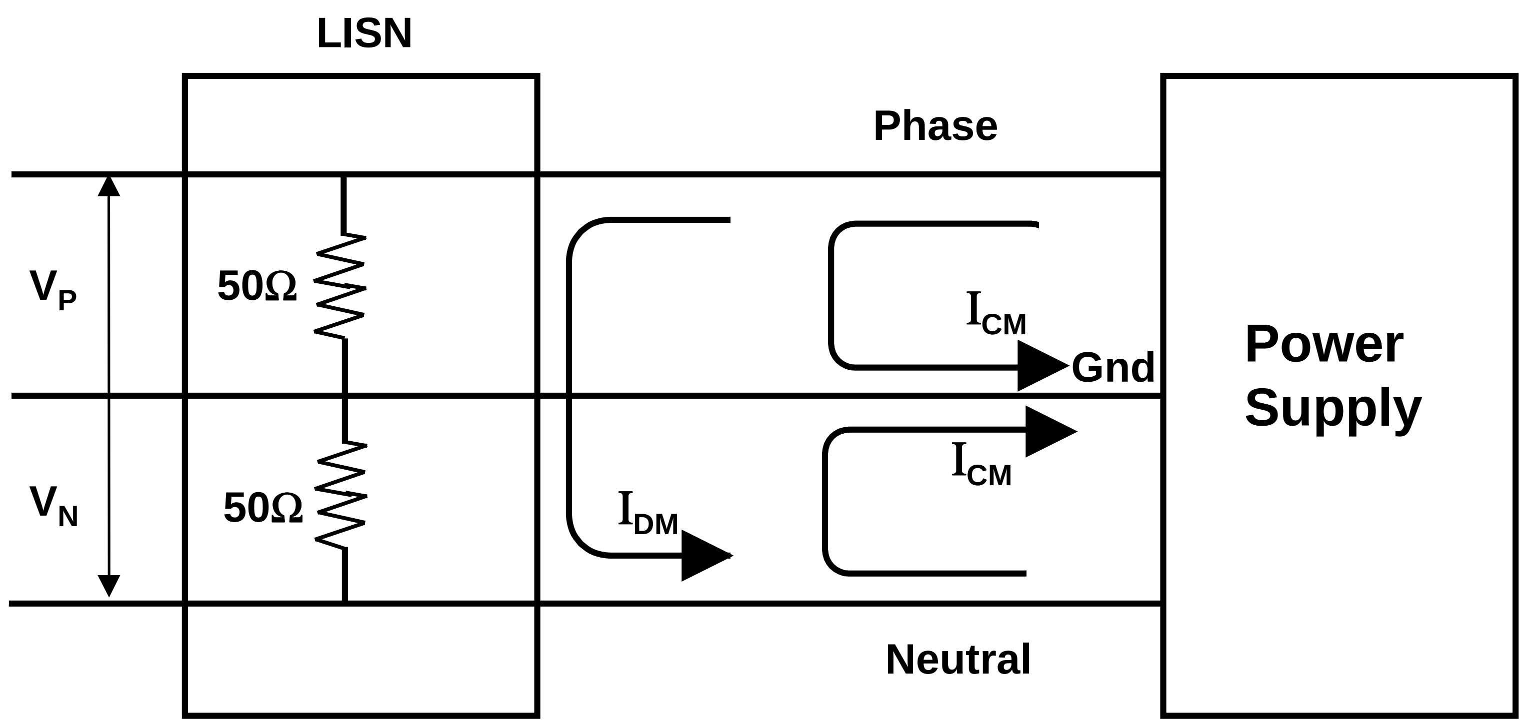
- In Troubleshooting Conducted Emission it Would be Helpful if we Could Separate the Common-Mode Current From the Differential-Mode Current

- This Would Allow Us to:

  — Optimize the Power Line Filter

  — Find the Cause of the Emission Within the Power Supply

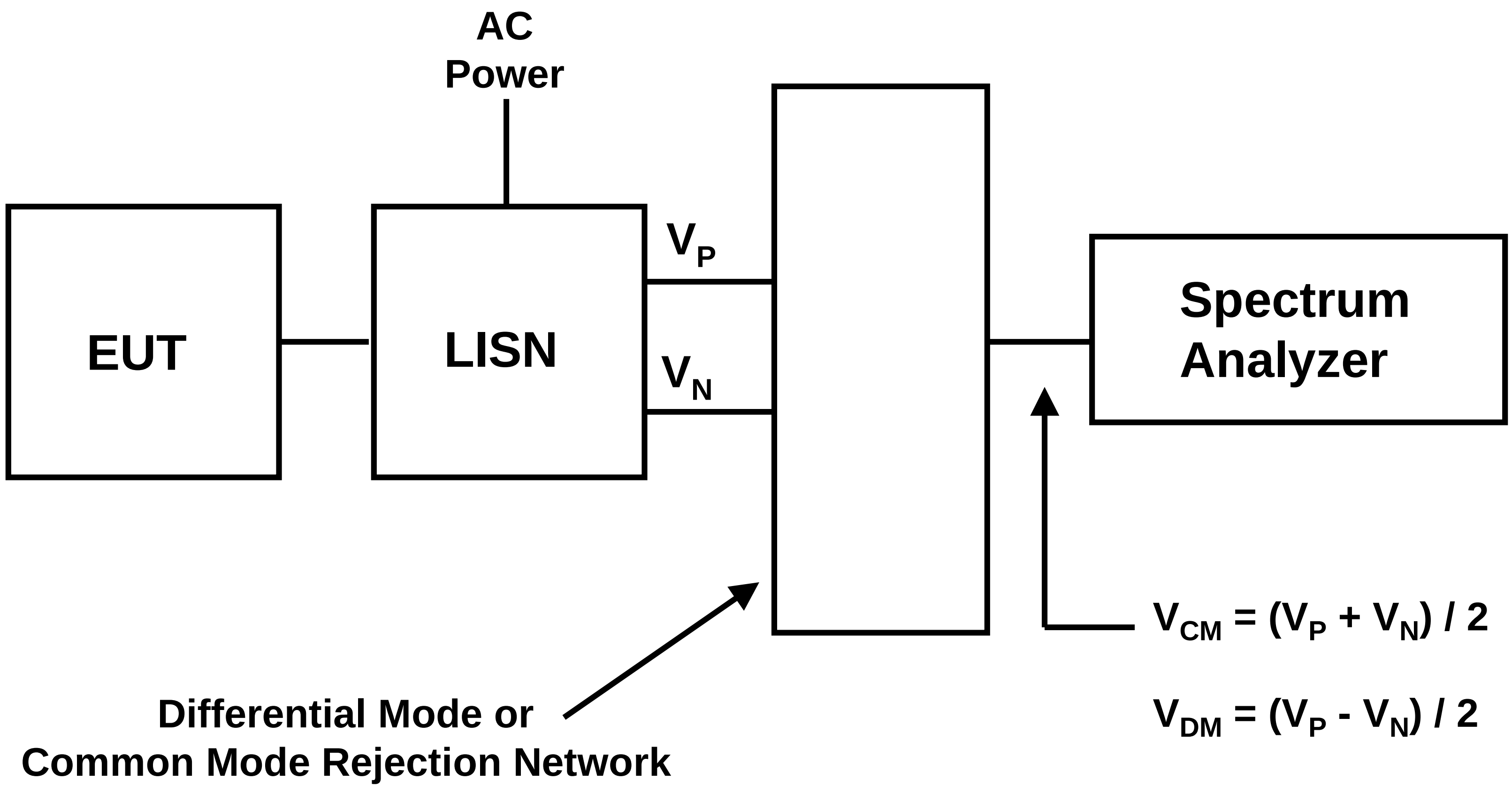
TOPOLOGY OF CONDUCTED EMISSION



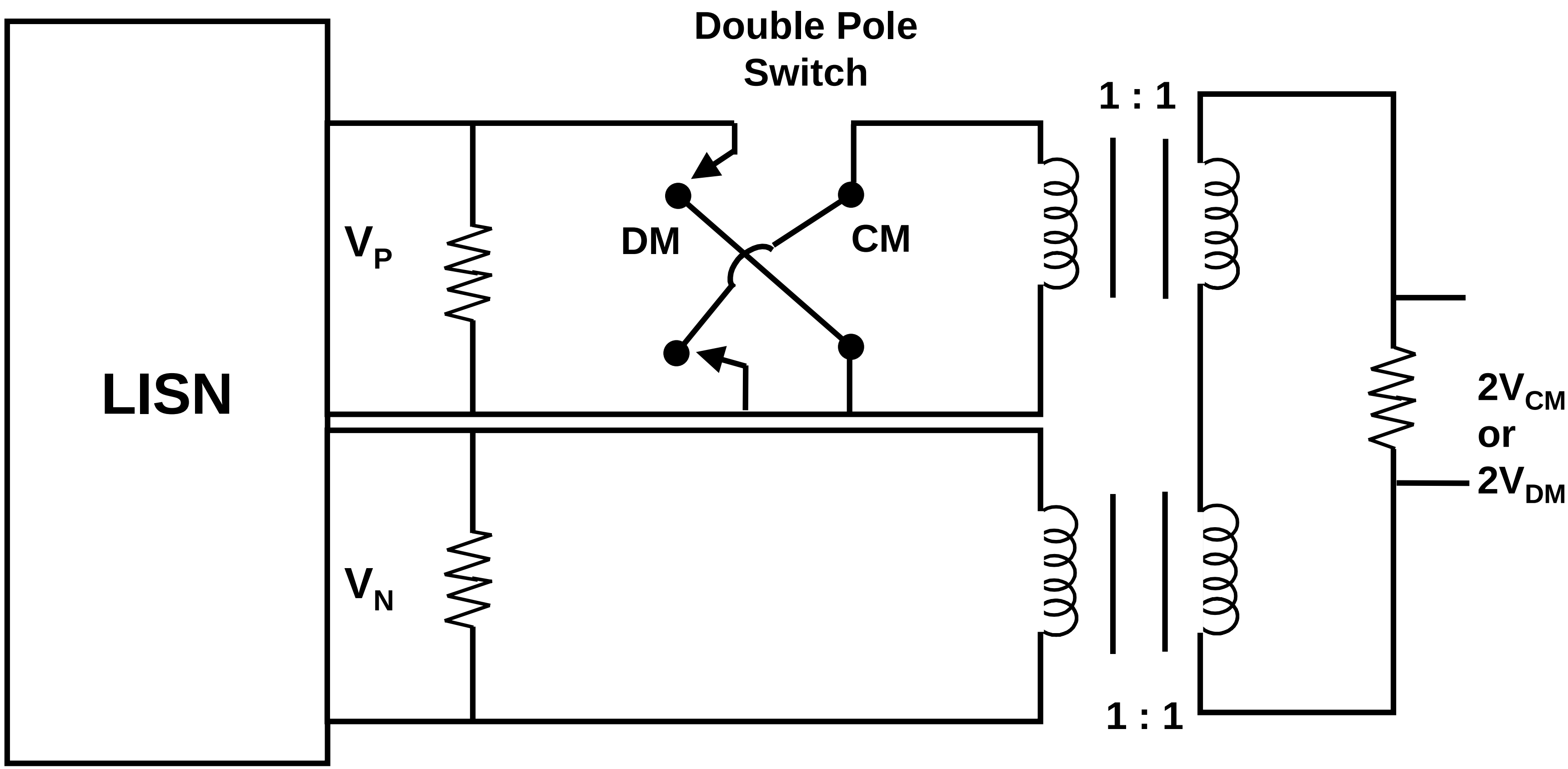
$V_P = 50\,(I_{CM} + I_{DM})$

$V_N = 50\,(I_{CM} - I_{DM})$

SEPARATING DIFFERENTIAL MODE AND COMMON MODE EMISSIONS

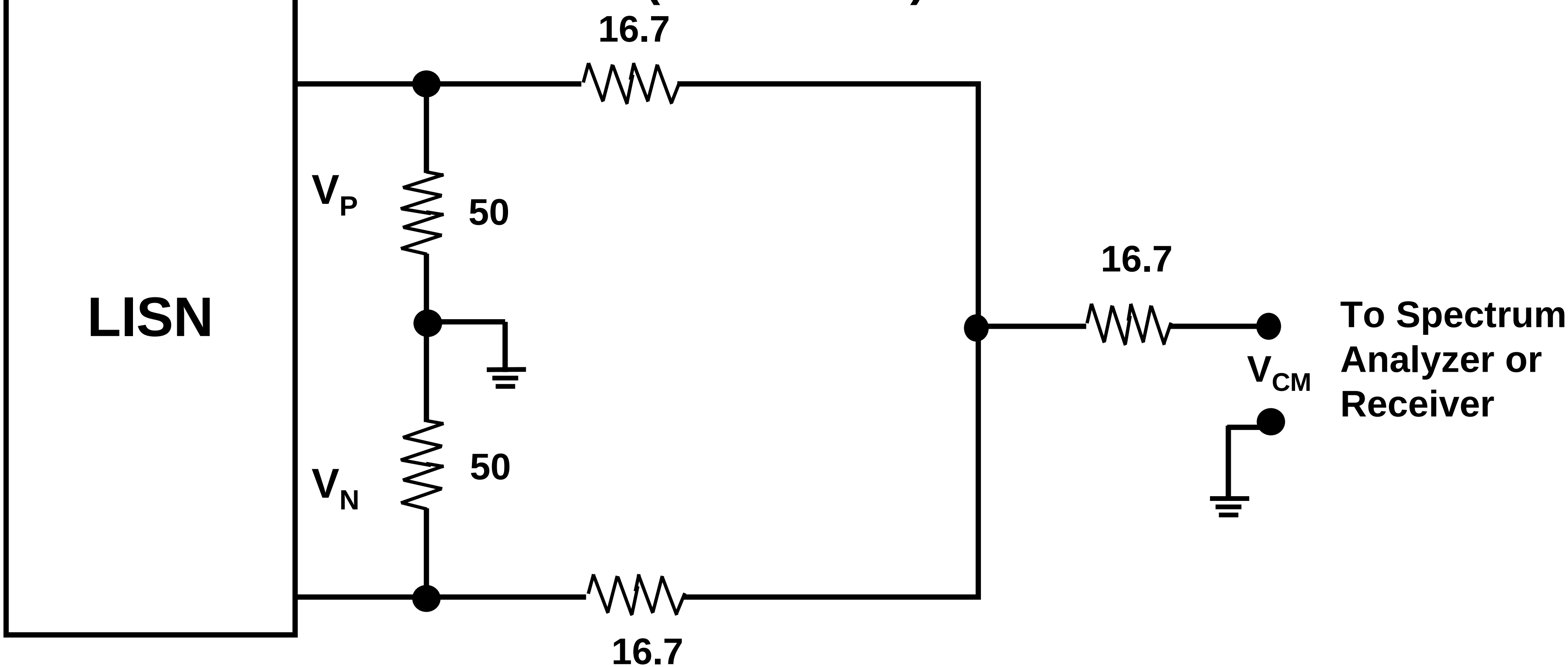


SEPARATION OF COMMON MODE AND DIFFERENTIAL MODE NOISE VOLTAGES



From: Paul, C. R. & Hardin, K. B., Diagnosis and Reduction of Conducted Noise Emissions, 1988 IEEE International Symposium on EMC, Seattle Washington, August 2-4, 1988

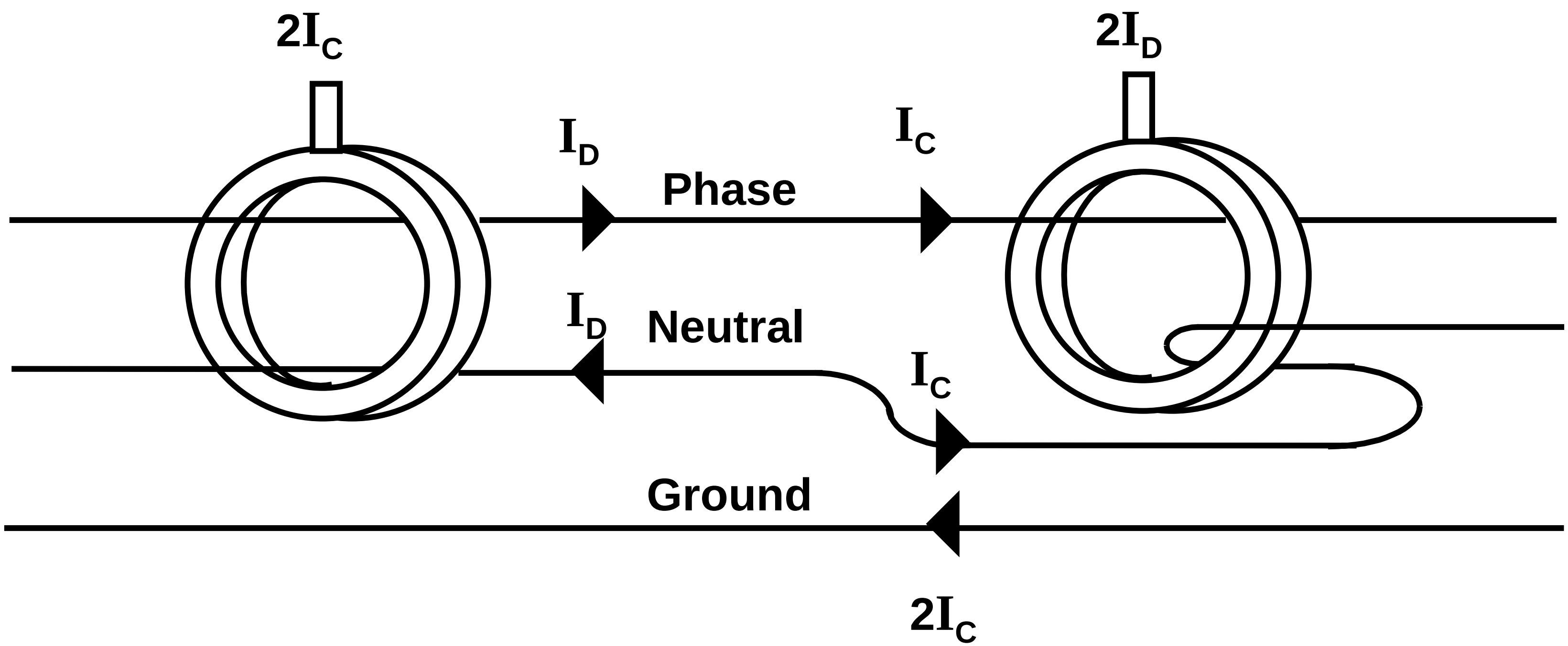
DIFFERENTIAL MODE REJECTION NETWORK
(LISN MATE)



All Resistor Values +/- 0.1%

From: Nave, M.J., Power Line Filter Design For Switched-Mode Power Supplies, Van Nostrand Rheinhold, 1991

ALTERNATIVE METHOD OF SEPARATING C-M AND D-M CURRENTS USING A CURRENT PROBE



Note: When Measuring D-M Noise Current Be Careful That the Intentional Power Line Current Does Not Saturate the Core of the Current Probe

SUMMARY

- Controlling C-M Emissions is Not “Black Magic”
- One Must, However, Be Able to Visualize the Noise Source and the Coupling Mechanism (The Invisible Schematic)
  - — The dV/dt Generator
  - — The Parasitic Capacitance
  - — The C-M Current Loop
- Once One Has an Understanding of the C-M Current Loop, the Required Control Techniques Become Fairly Straightforward and Obvious
- C-M Currents Must be Returned Locally and Compactly (Small Loop Area)
- Proper Use of Filtering, Grounding, and Shielding Will Solve Most C-M Emission Problems

REFERENCES

- Ott, H. W., *Noise Reduction Techniques in Electronic Systems*, John Wiley, 1988
- Nave, M. J., *Power Line Filter Design for Switched-Mode Power Supplies*, Van Nostrand Rheinhold, 1991
- Fluke, J. C., *Controlling Conducted Emissions by Design*, Van Nostrand Rheinhold, 1991
- Knurek, D. F., Reducing EMI in Switching Supplies, *Powertechnics Magazine*, August 1989
- Paul, C. R. & Hardin, K. B., Diagnosis and Reduction of Conducted Noise Emissions, *1988 IEEE International Symposium on EMC*, Seattle Washington, August 2-4, 1988