

# **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

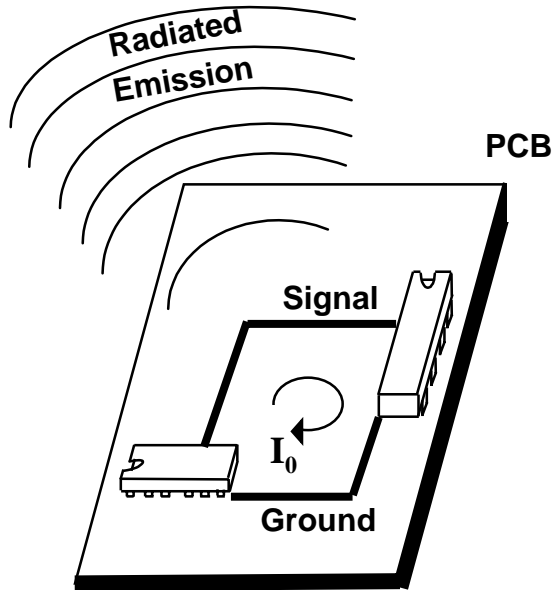
- Involves the Normal Operation of the Circuit
- Currents Flowing Around Loops
- Is Documented
  - Schematics
  - PCB Layout
  - Wiring Diagrams
- Is Easy to Understand

### ● 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

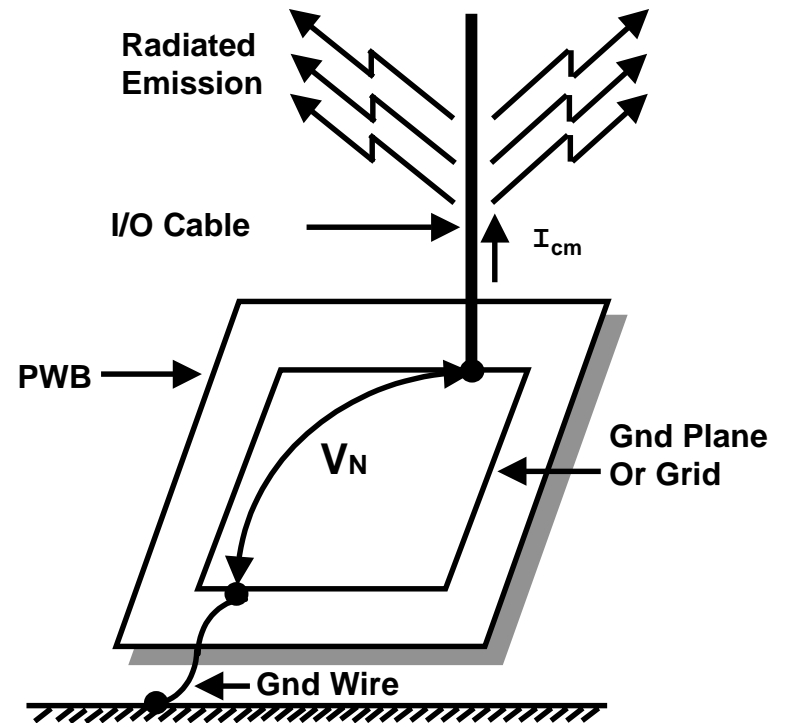
# RADIATION MECHANISMS

## DIFFERENTIAL-MODE RADIATION



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

## COMMON-MODE RADIATION

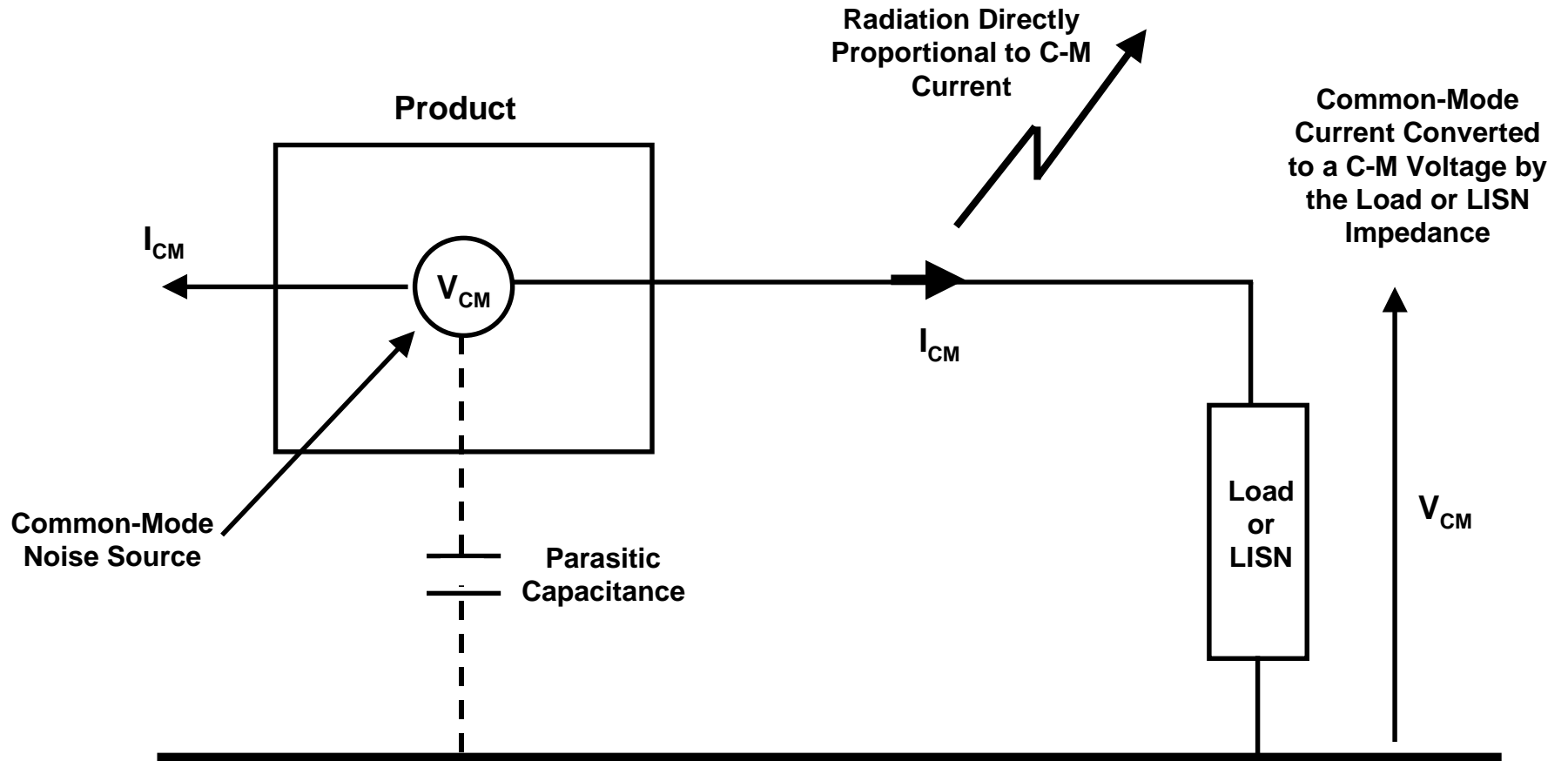


$$E = K_2 f L I_{cm}$$

## BASIC ANTENNA TYPES

<u>Antenna Type</u>	<u>Radiation Mechanism</u>	<u>Electromagnetic Field</u>
Loop	Differential-Mode	Magnetic Field
Dipole	Common-Mode	Electric Field

# RADIATED VERSUS CONDUCTED C-M EMISSION

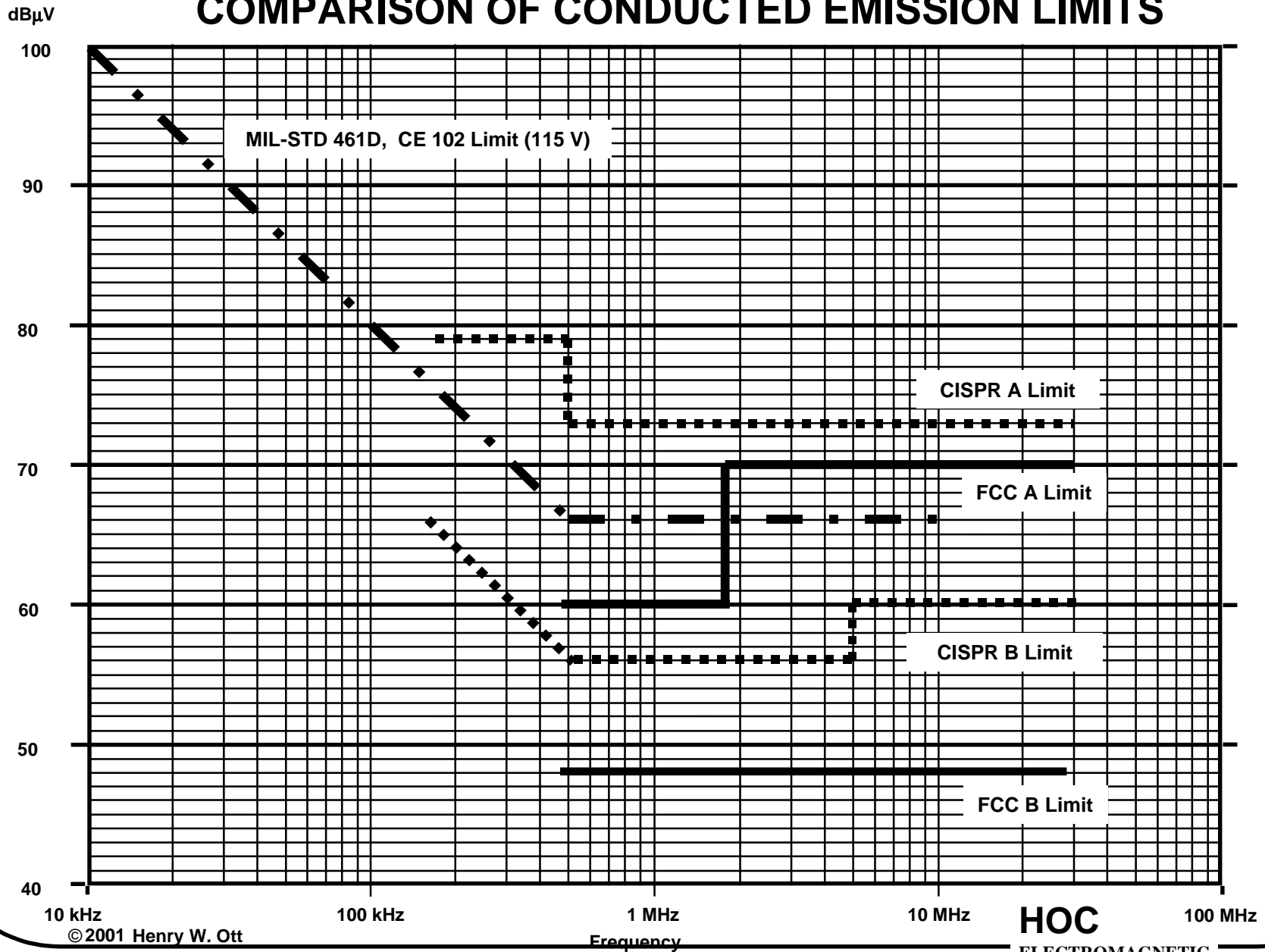


## **EMC REGULATIONS PERTAINING TO C-M EMISSIONS**

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



# COMPARISON OF CONDUCTED EMISSION LIMITS



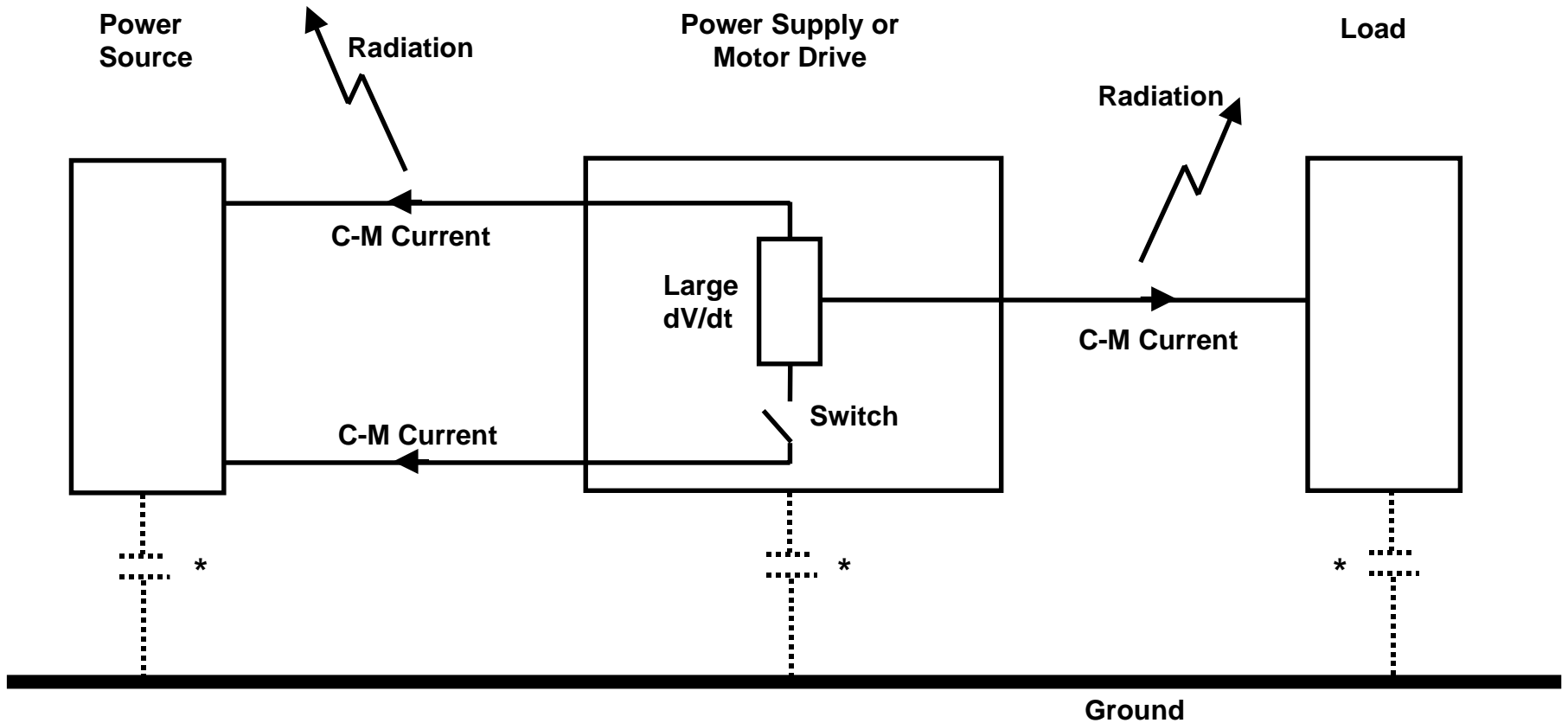
## HOW MUCH C-M CURRENT IS A PROBLEM (Based on FCC Requirements)

<u>Frequency</u>	<u>Class A</u>	<u>Class B</u>
<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

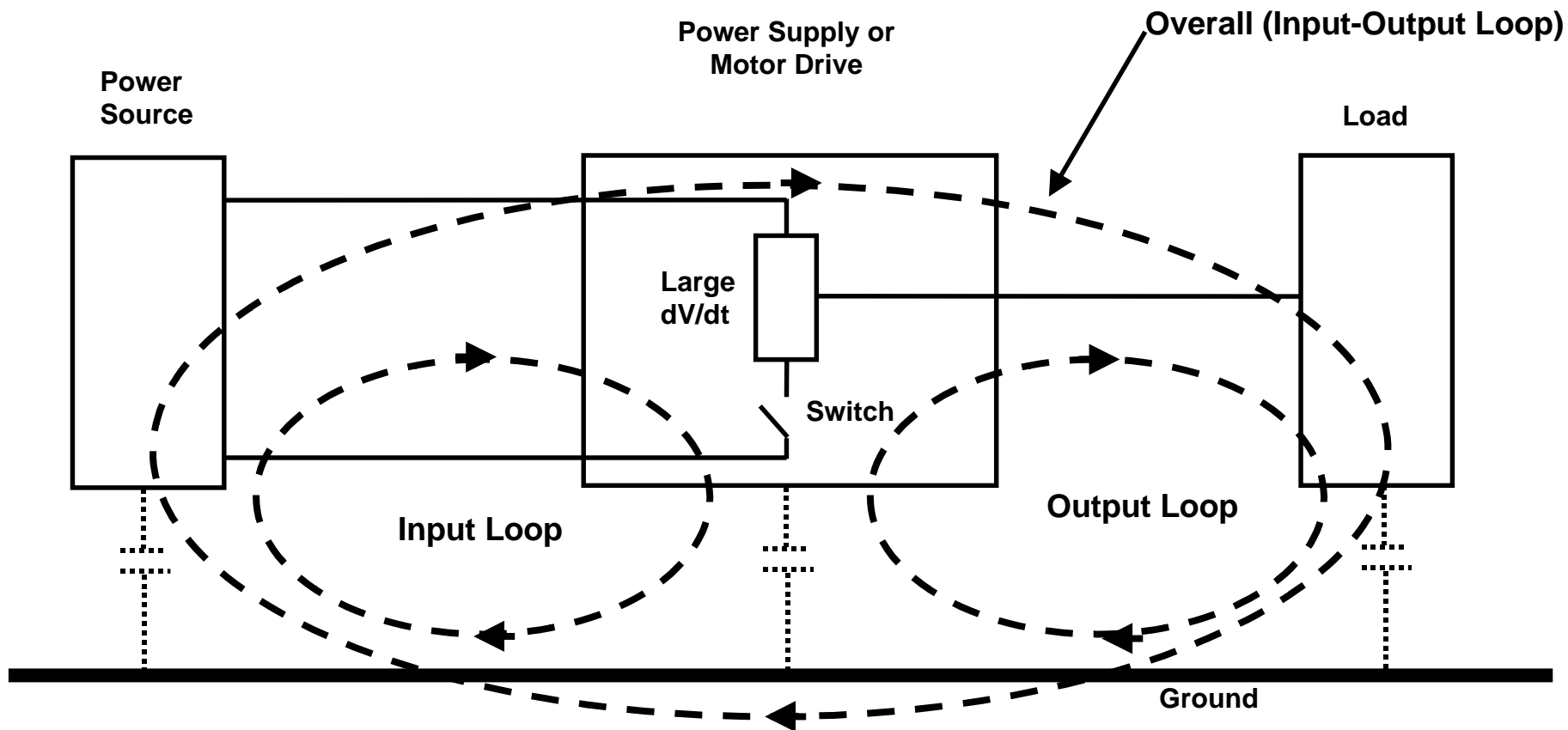
\*\* Based on Radiated Emission Limits

# 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

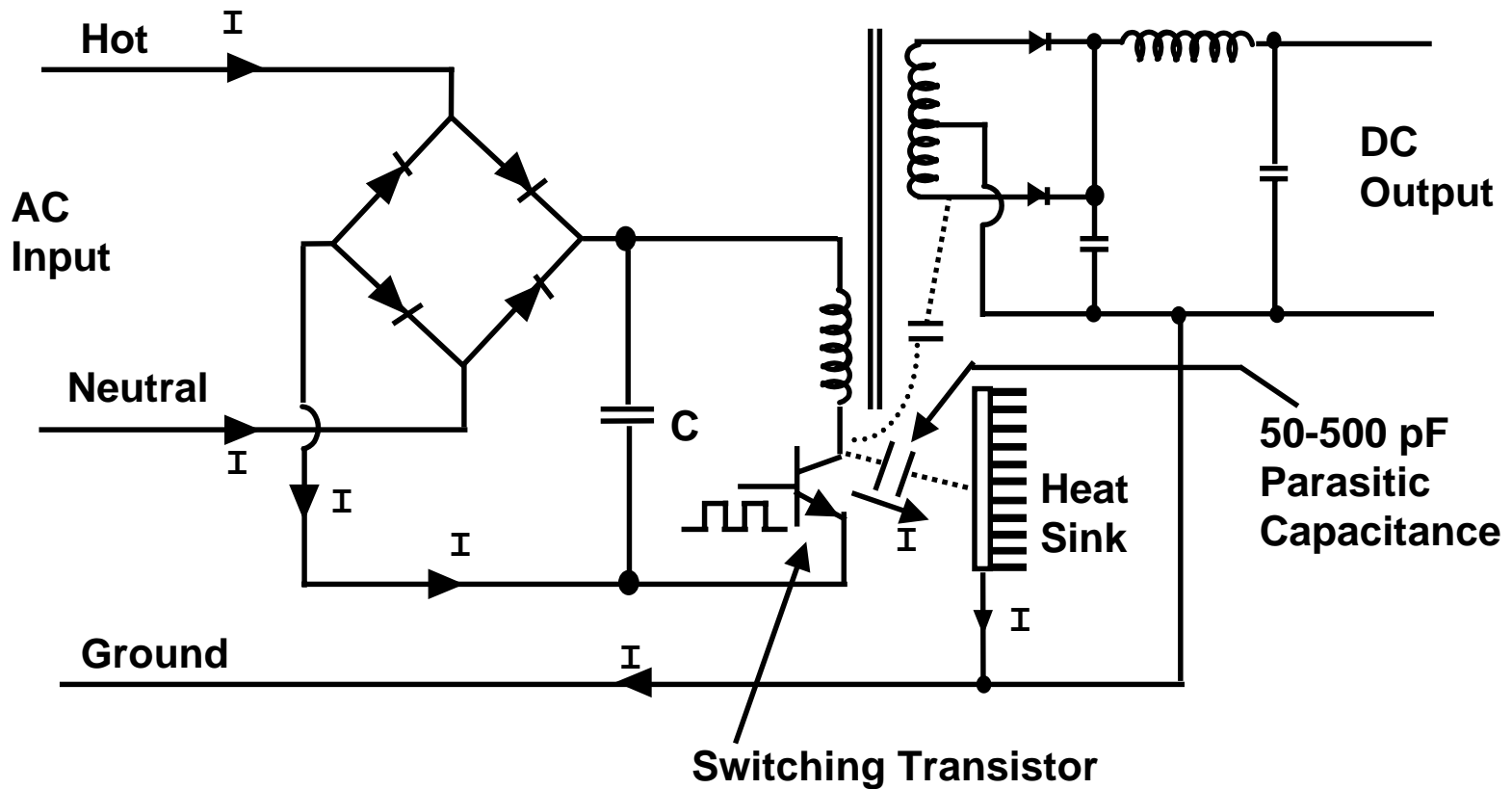
- **Consists of:**
  - the  $dV/dt$  Generator, and
  - the Parasitic Capacitance
- **You Should be Able to Find and Visualize These Components**
- **Once the Invisible Schematic Components are Identified, the Required Control Techniques Become Fairly Straightforward and Obvious. They are not “Black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

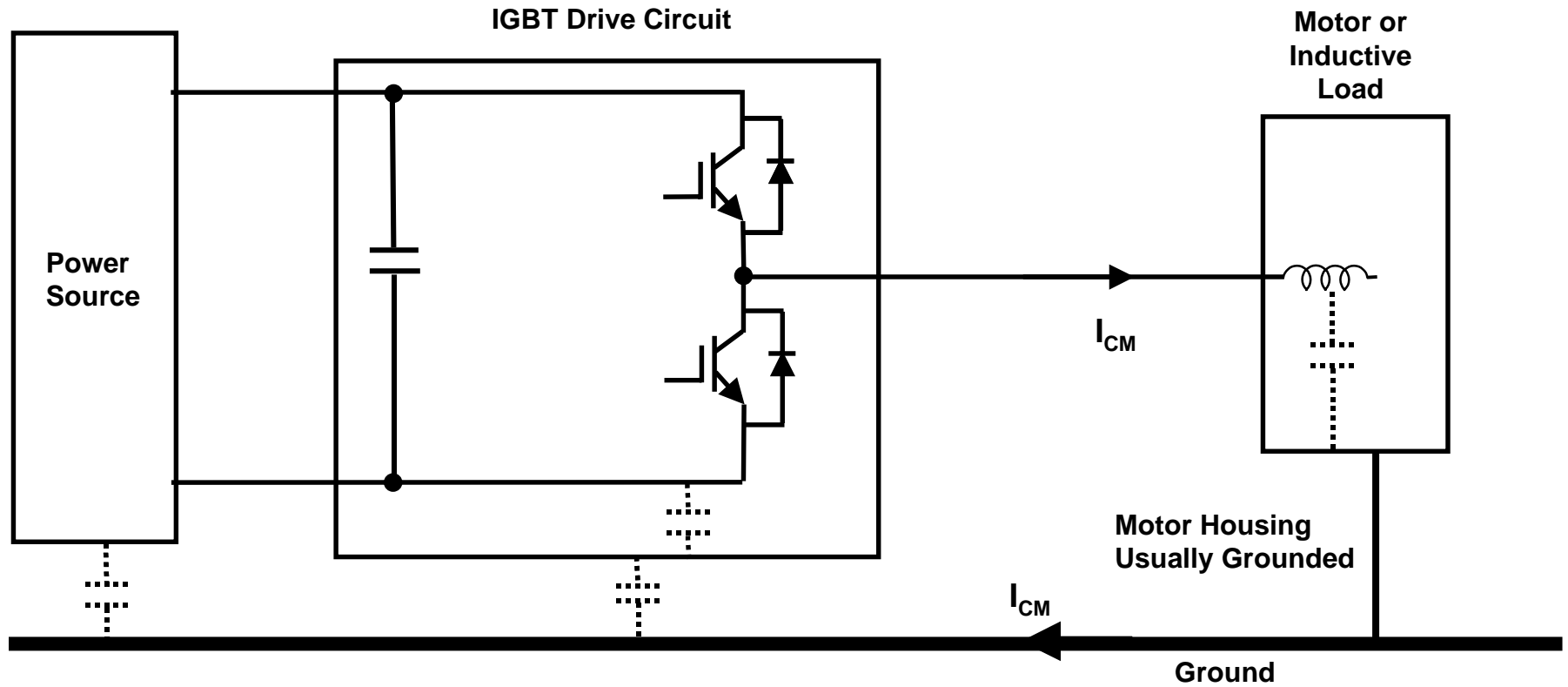
\* Usually the Switching Transistors

# SWITCHING POWER SUPPLY CONDUCTED EMISSION, COMMON-MODE



$I = \text{C-M Noise Current}$

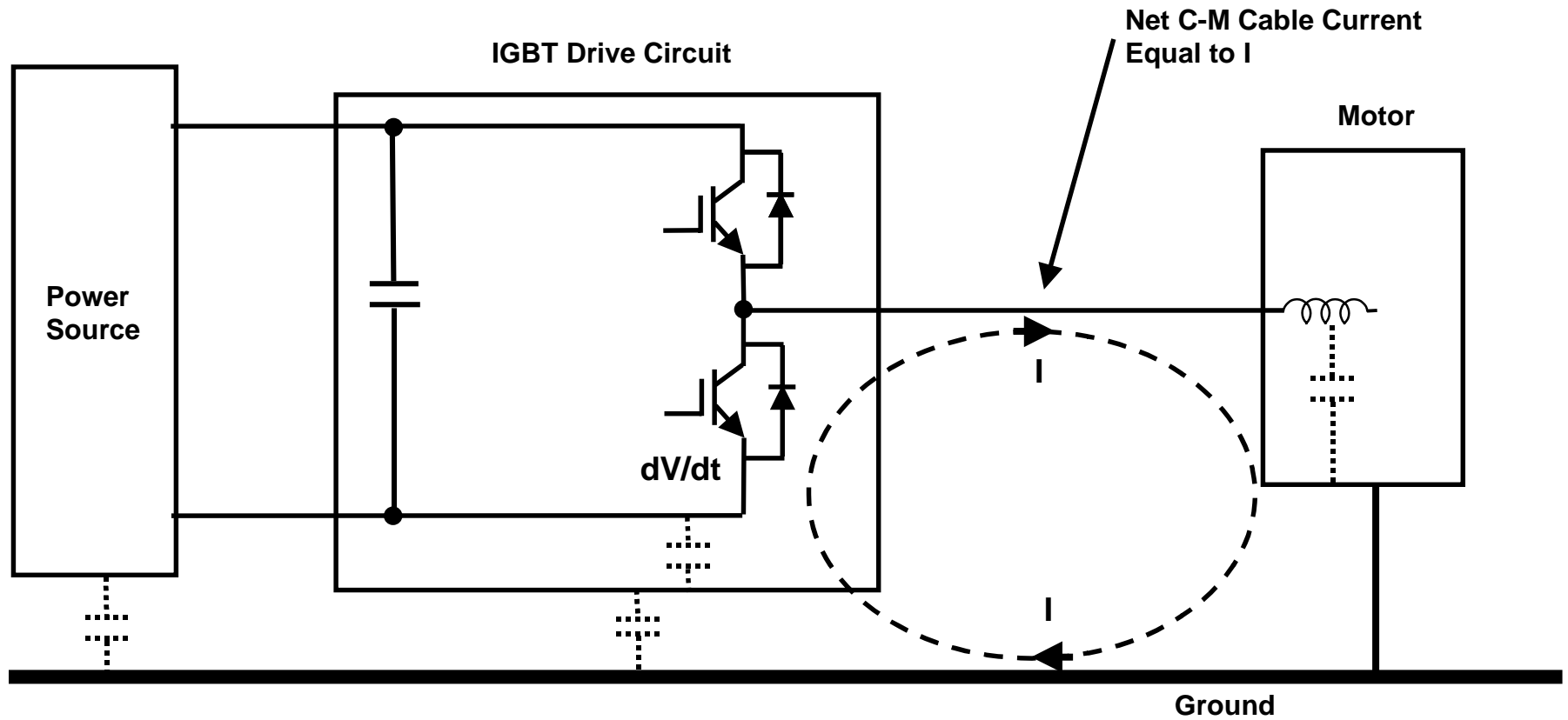
# BASIC IGBT MOTOR DRIVE



## 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



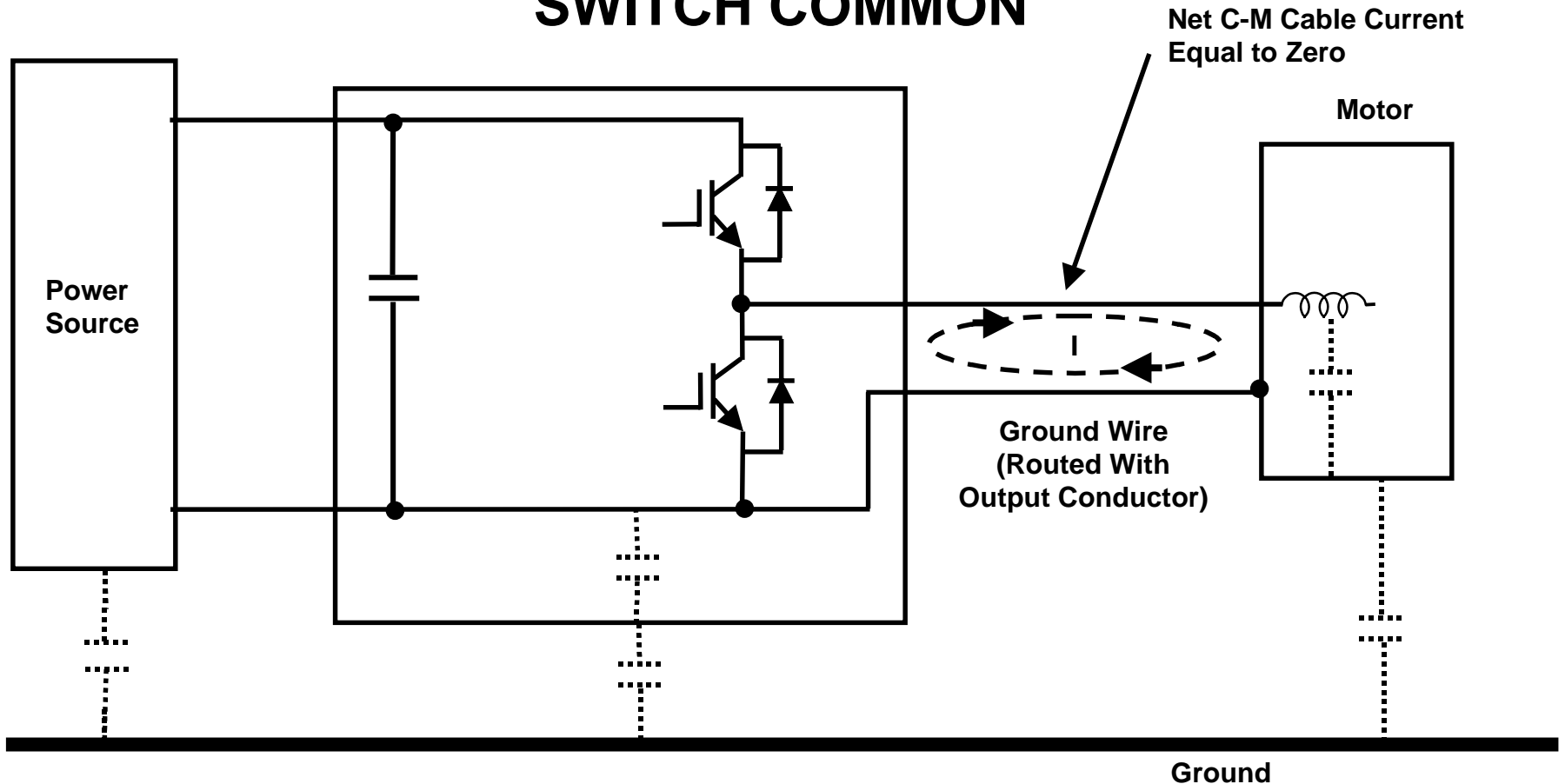
## **THE BASIC IGBT MOTOR DRIVE PROBLEM (LOAD SIDE C-M CURRENT)**

- **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



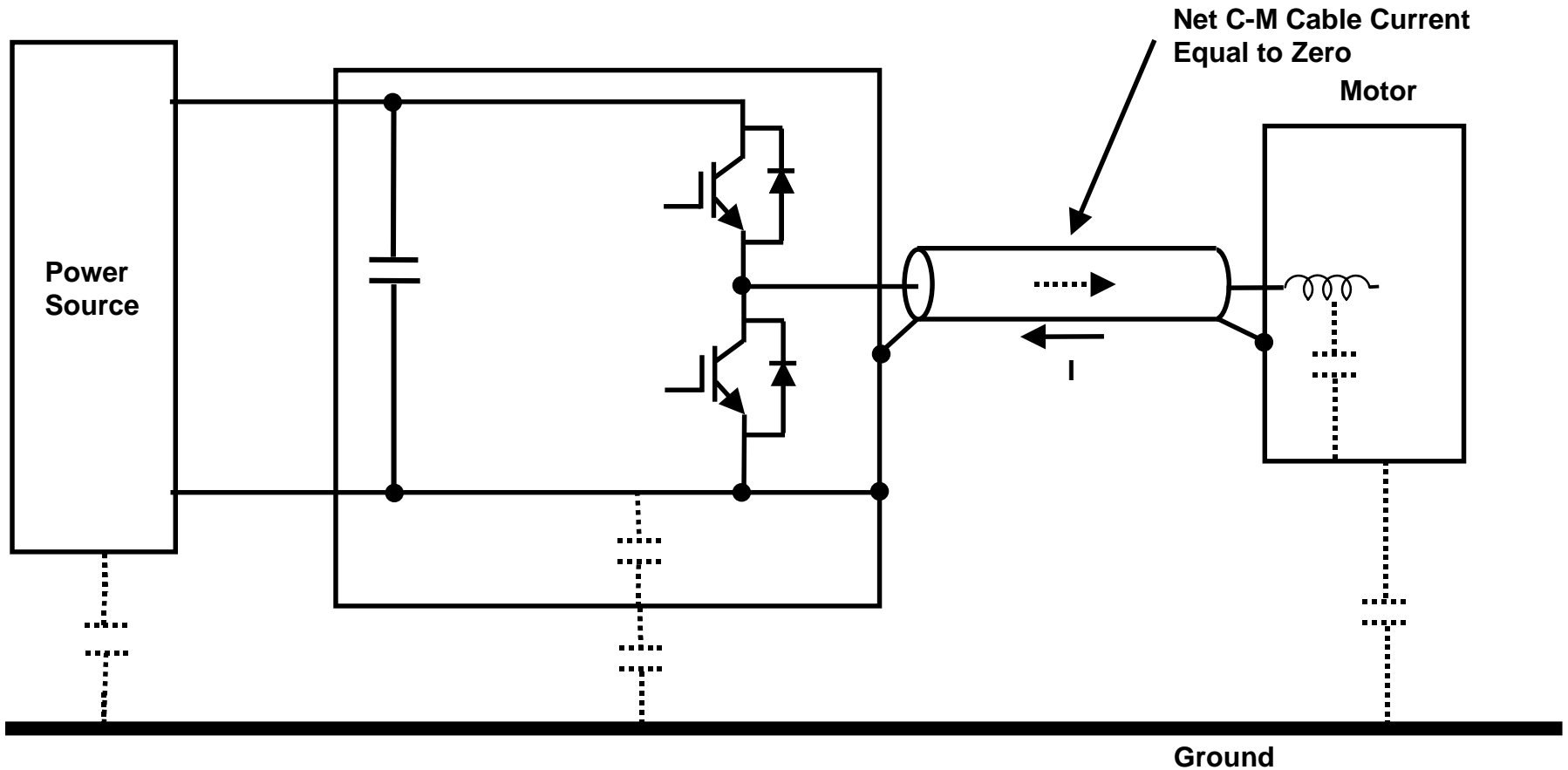
This is the Ideal Solution But May Be Difficult to Implement

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

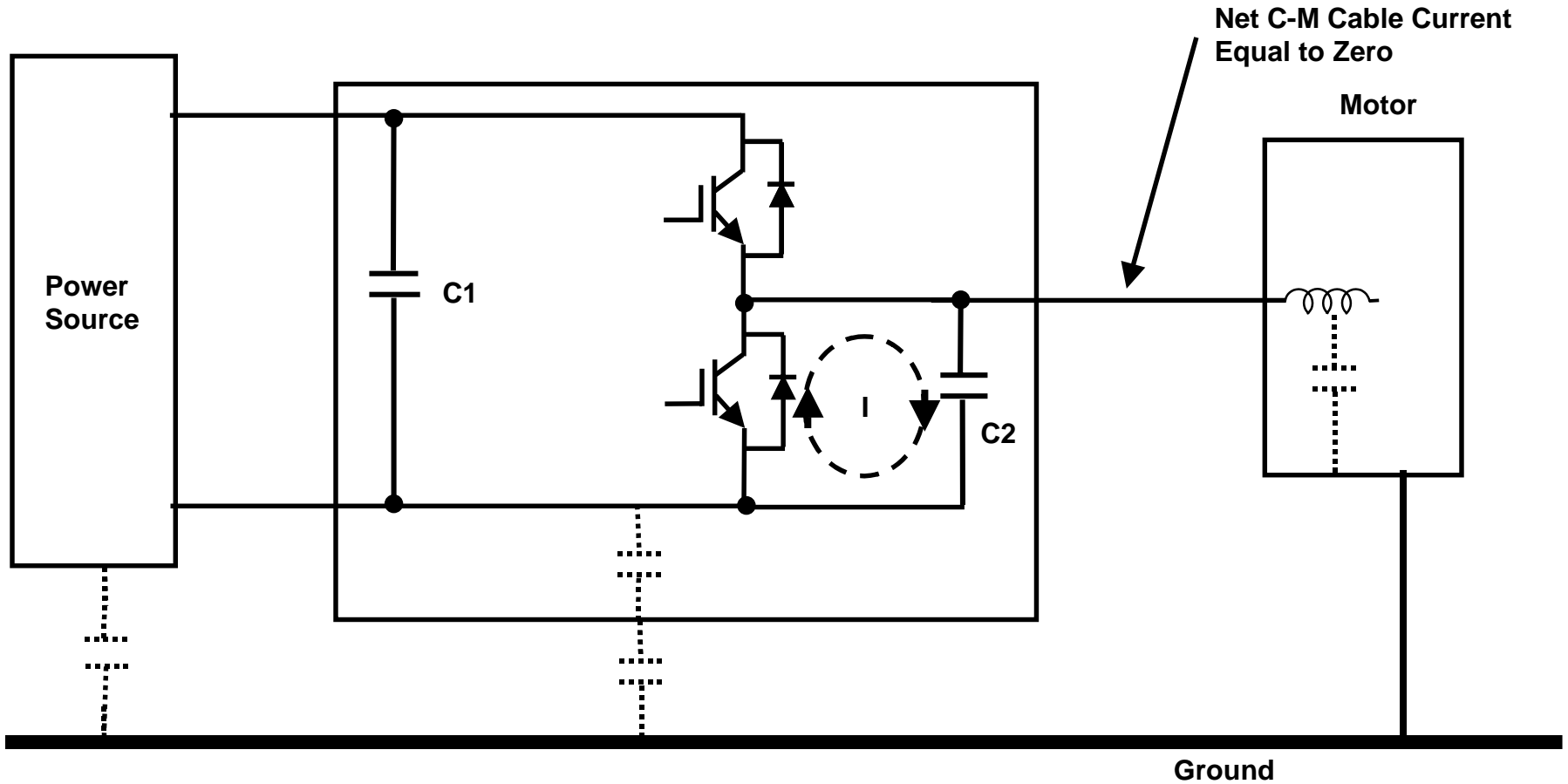
Capacitor Value Limited by Leakage Current Requirements. Therefore, Not Very Effective at Low Frequencies

# SHIELDED CABLE SOLUTION



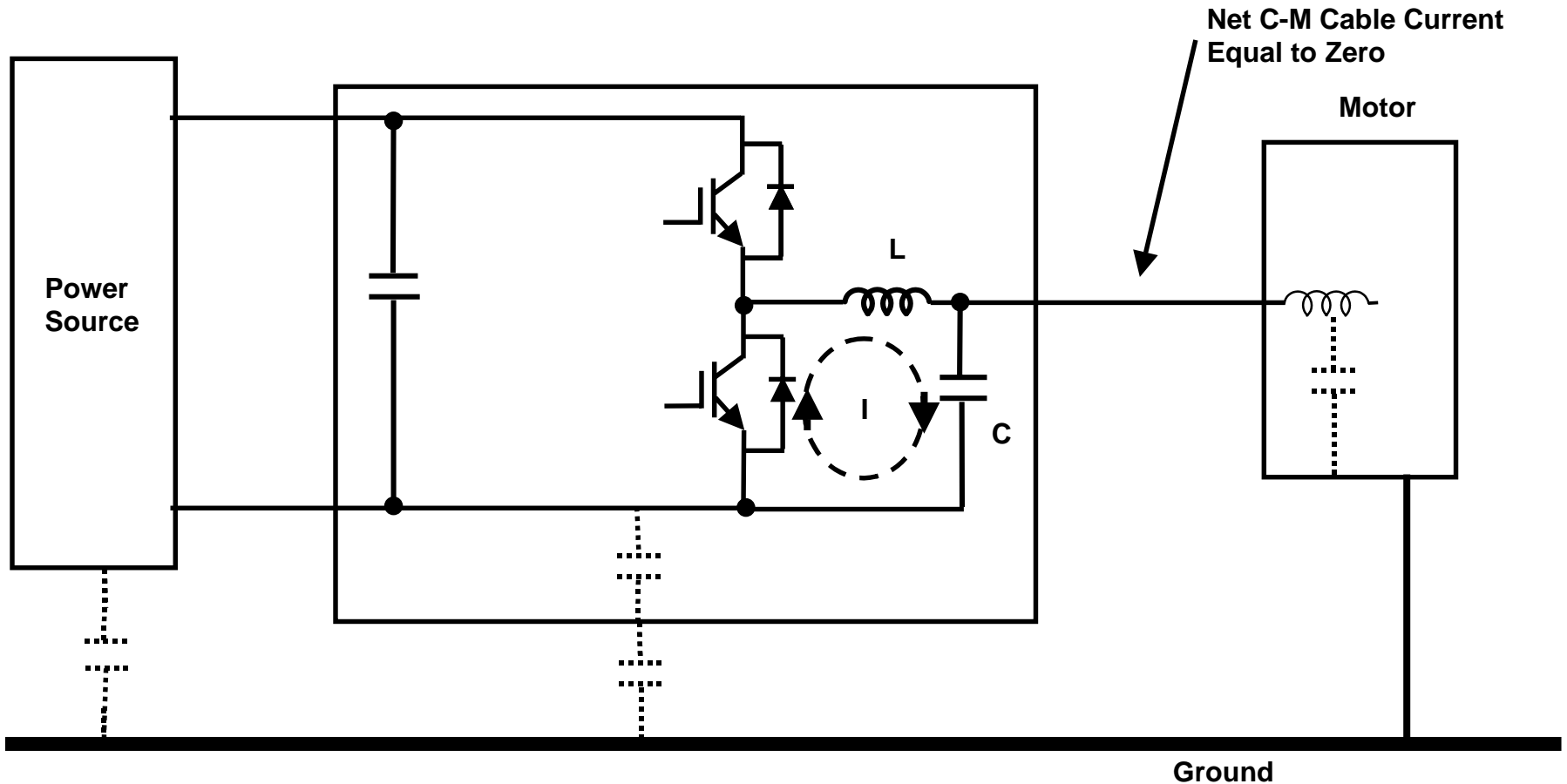
Similar to the Ground Wire Described Previously, But More Effective For Radiated Emission  
 Shield Must Be Connected to Motor Housing on One End and to the Switch Common on the Other End  
 Shield May Be Terminated With a Capacitor on One End as a Compromise

# CAPACITOR FILTER SOLUTION



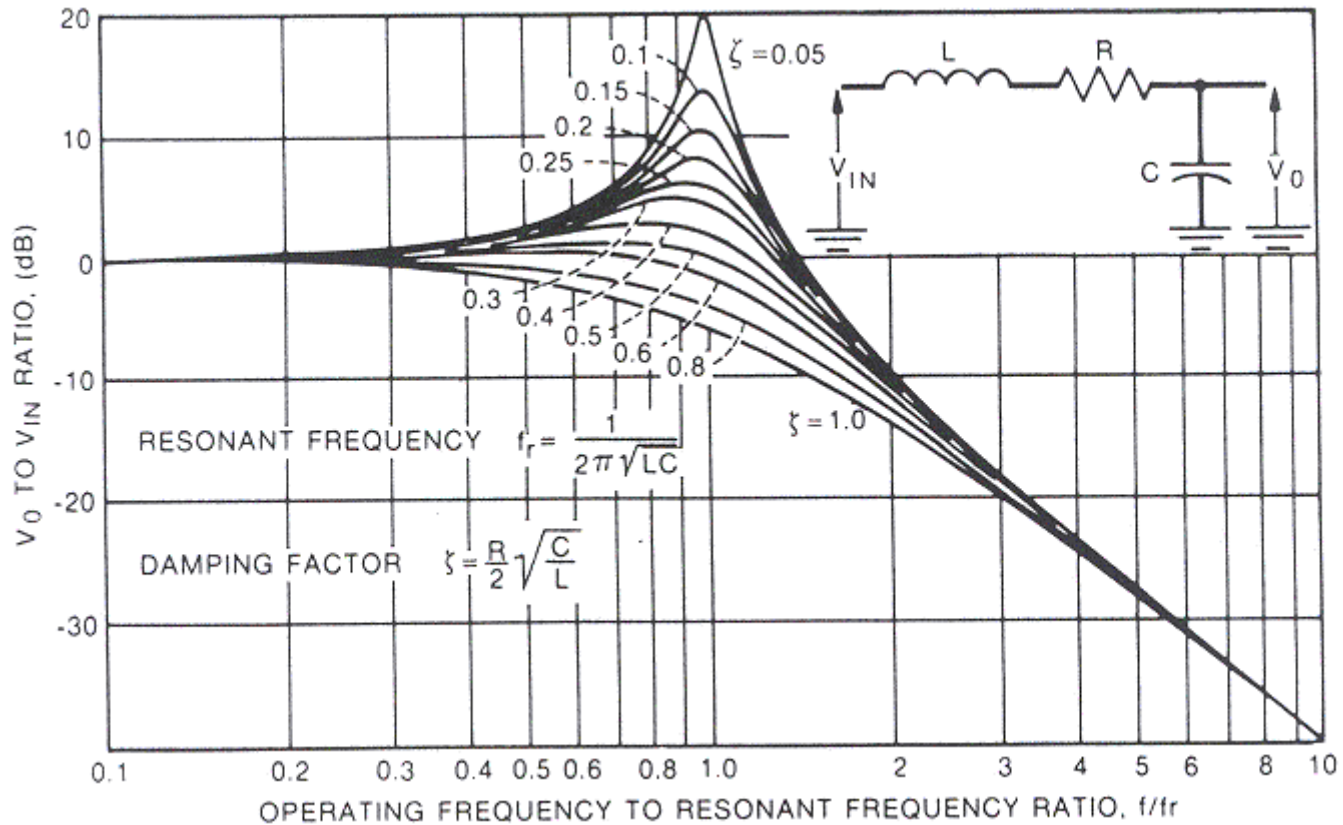
**Often Tried, However, it is a Good Way to Destroy the IGBT's  
You Are Dumping the Contents of a Large Capacitor (C1) Into a Smaller Capacitor (C2)  
Through a Low Impedance Switch With No Current Limiting**

## 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)

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

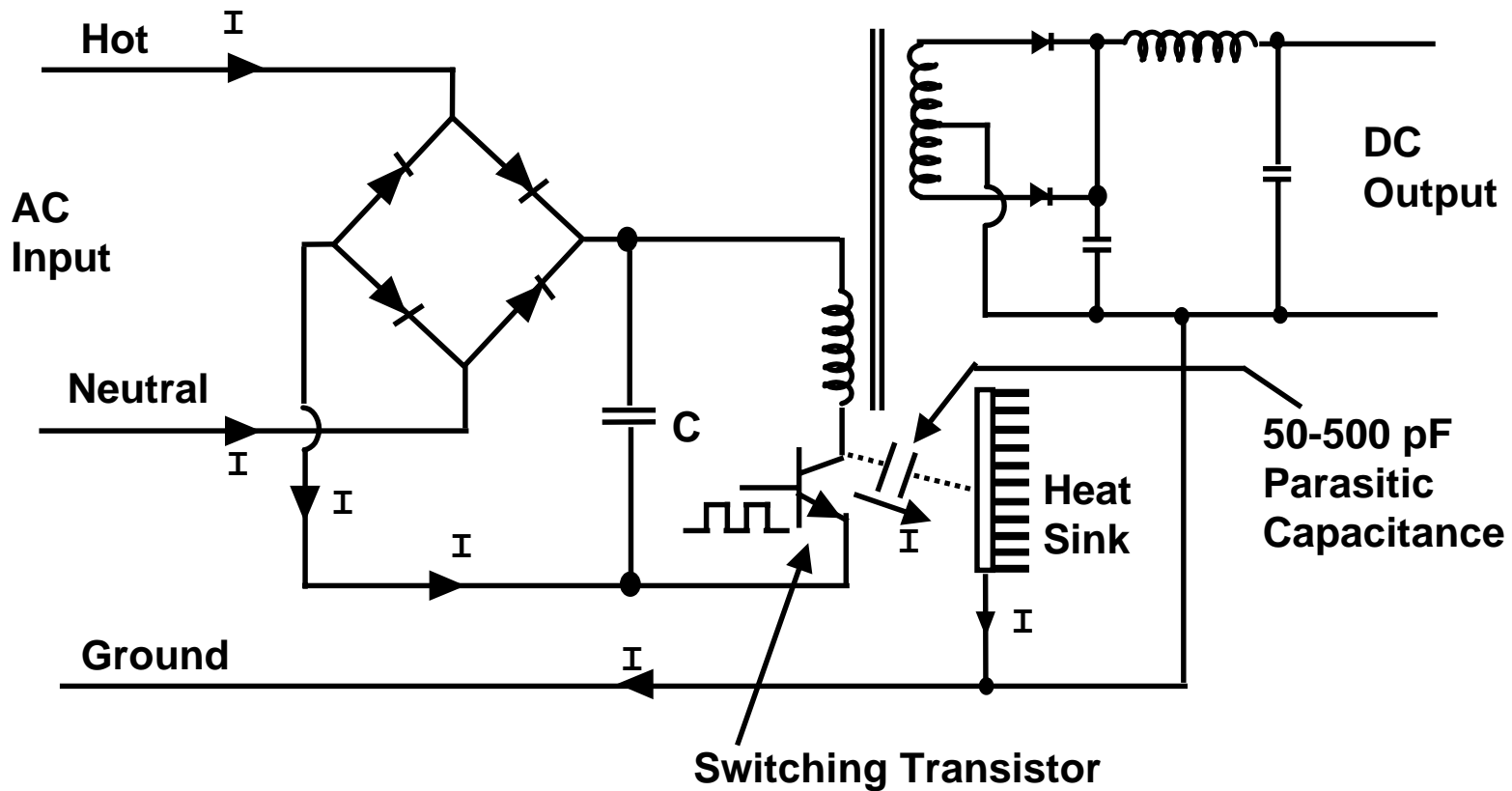
## **SWITCHING POWER SUPPLY NOISE SOURCES AND COUPLING PATHS**

- **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

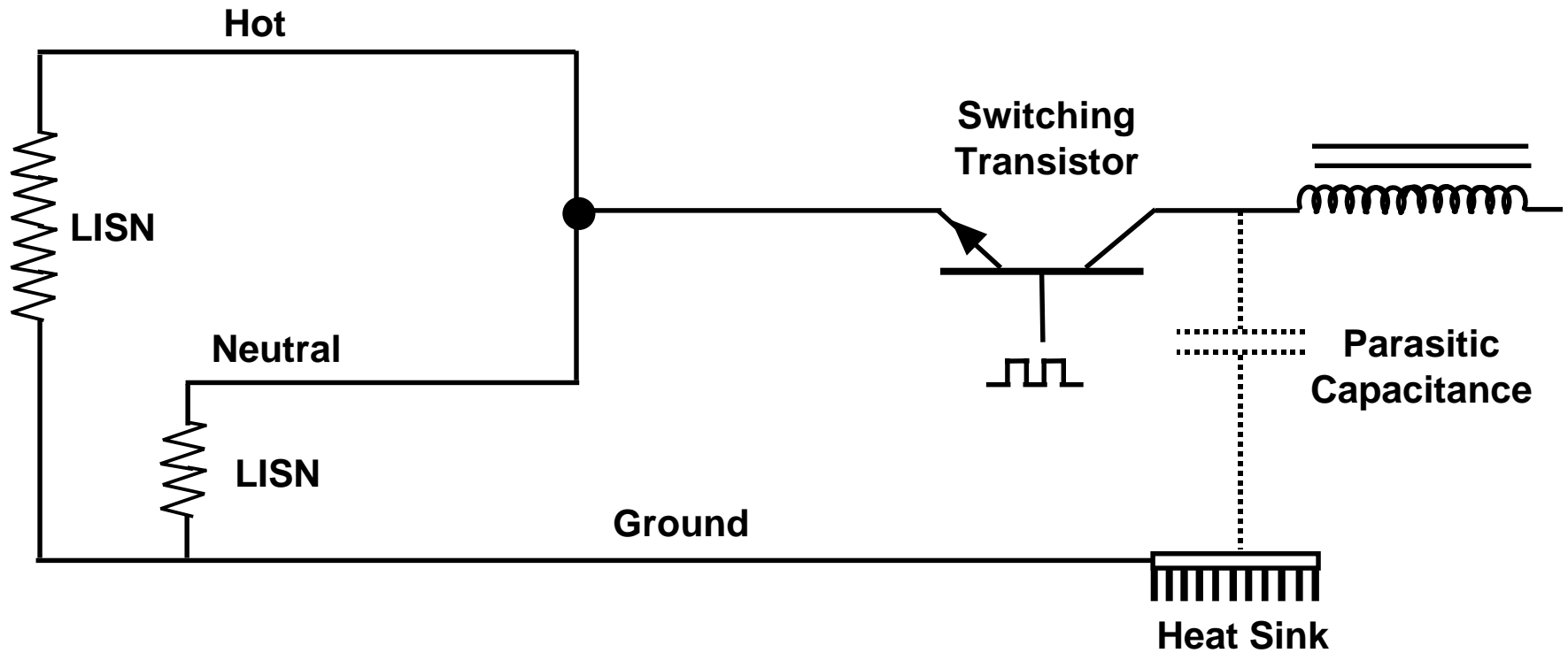
- The Function of a Regulated Power Supply is to Keep the Output Voltage Constant
- If the Output Voltage is Constant, We Can Assume That the Output Current and Output Power Are Also Constant (Assuming a Fixed Load Impedance)
- If the Output Power is Constant, the Input Power Must Also be Constant
- Hence, the Input  $V \times I$  Product Must be Constant
- If the Input Voltage Decreases, the Input Current Must Increase in Order to Maintain a Constant  $V \times I$  Product
- Therefore, the Power Supply Has a Negative Input Impedance (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



$I = \text{C-M Noise Current}$

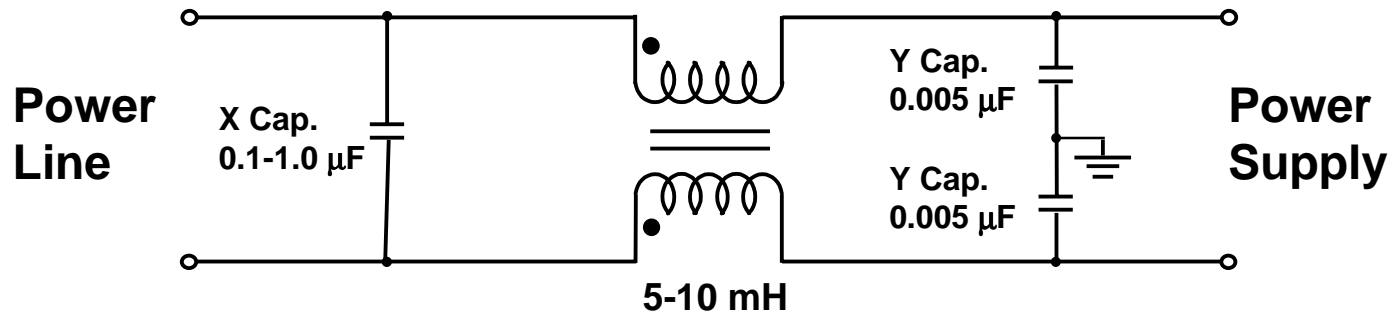
# COMMON MODE EQUIVALENT CIRCUIT OF SWITCHING POWER SUPPLY



## THE SWITCHING POWER SUPPLY PROBLEM

- Operating Voltage Level Within Power Supply = 150 V.
- Maximum Conducted Emission (Class B) = 250  $\mu$ V.
- $250 \mu\text{V} / 150 \text{ V} = 1.67 \times 10^{-6} = -116 \text{ dB}$
- The Allowable Conducted Emission Level is One Millionth of the Operating Level
- Required Suppression = 120 dB

## TYPICAL POWER LINE FILTER



**Note:**

**X Cap. Affects Differential-Mode**

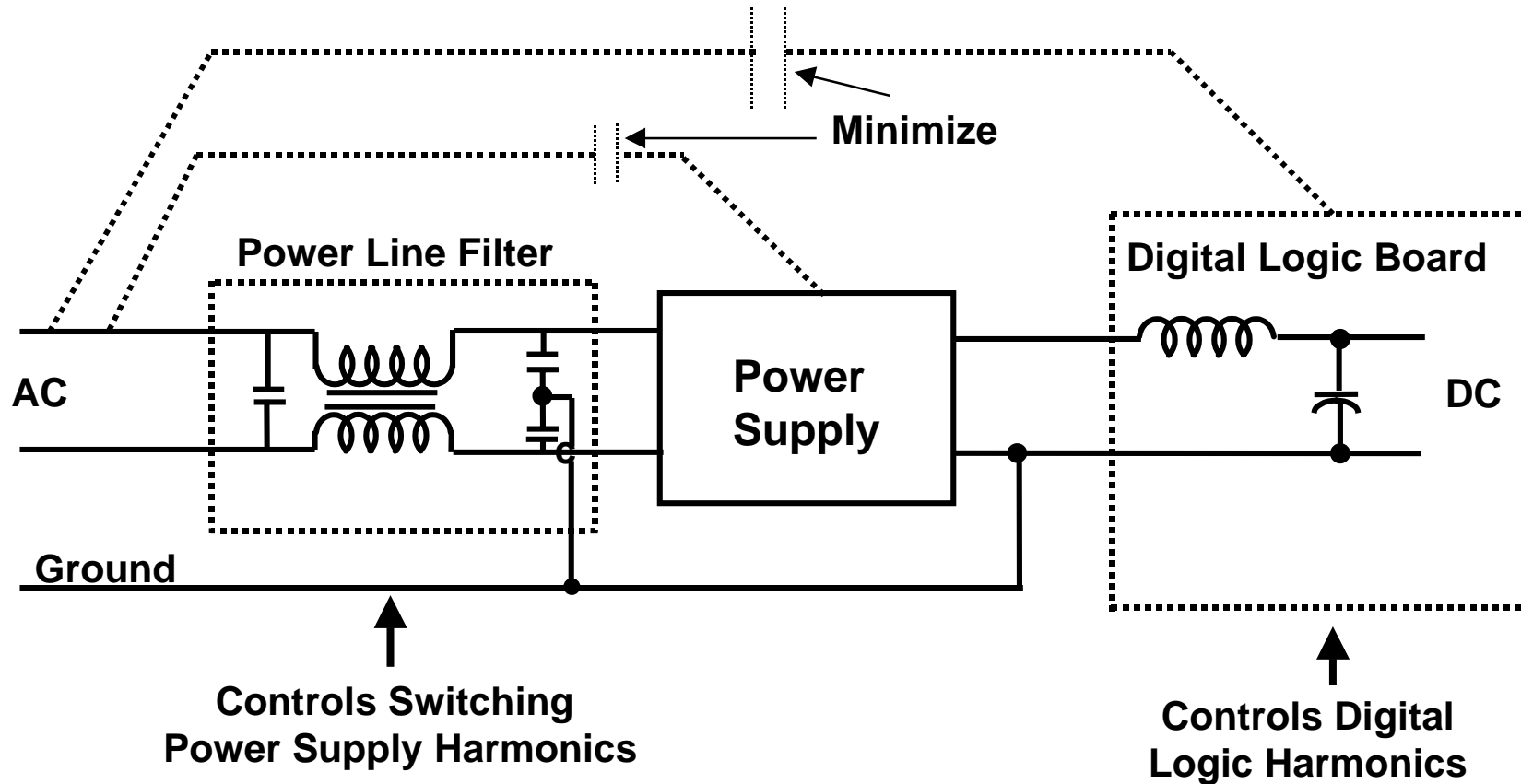
**Y Cap. Affects Common-Mode, The Series Combination Affects Differential-Mode**

**Choke Affects Common-Mode, Leakage Inductance Affects Differential-Mode**

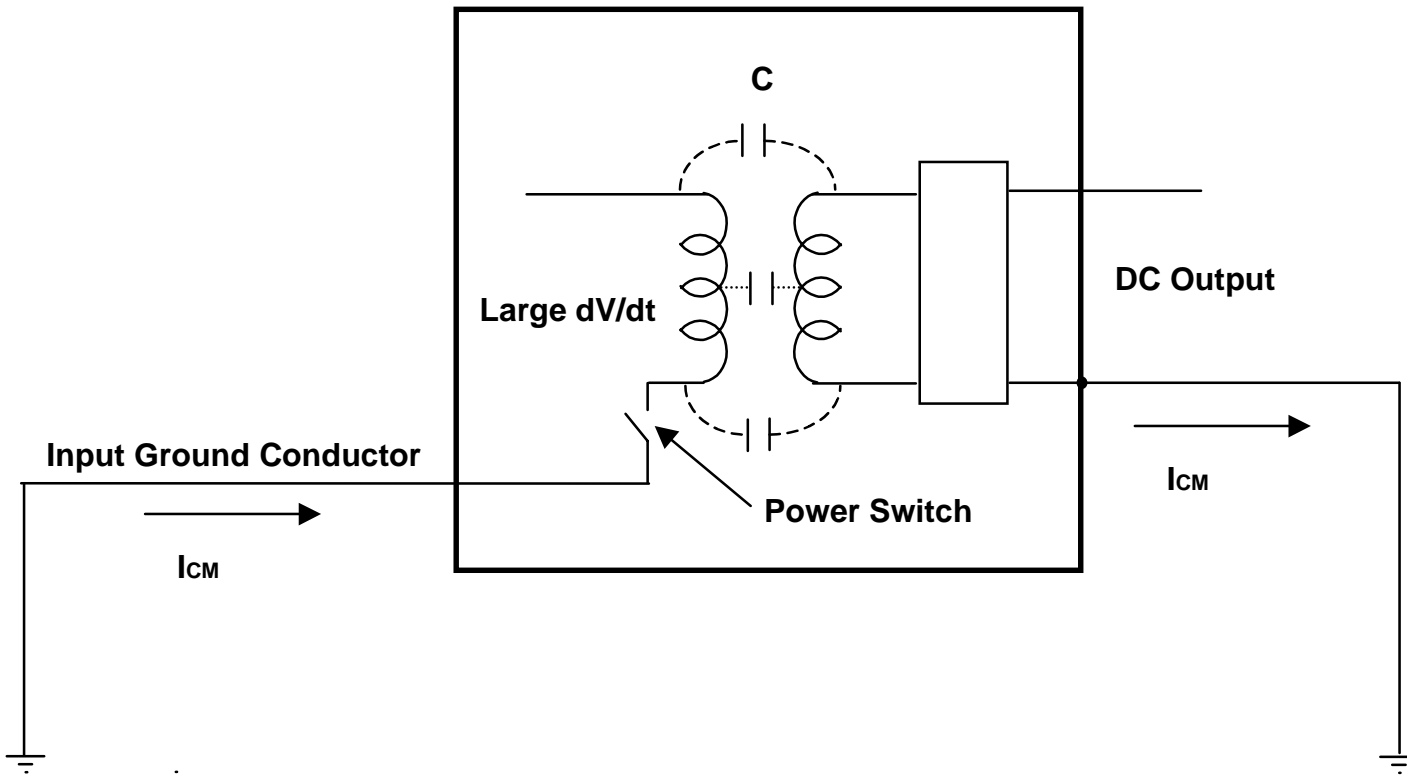
# **AC POWER LINE FILTERS**

**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.**

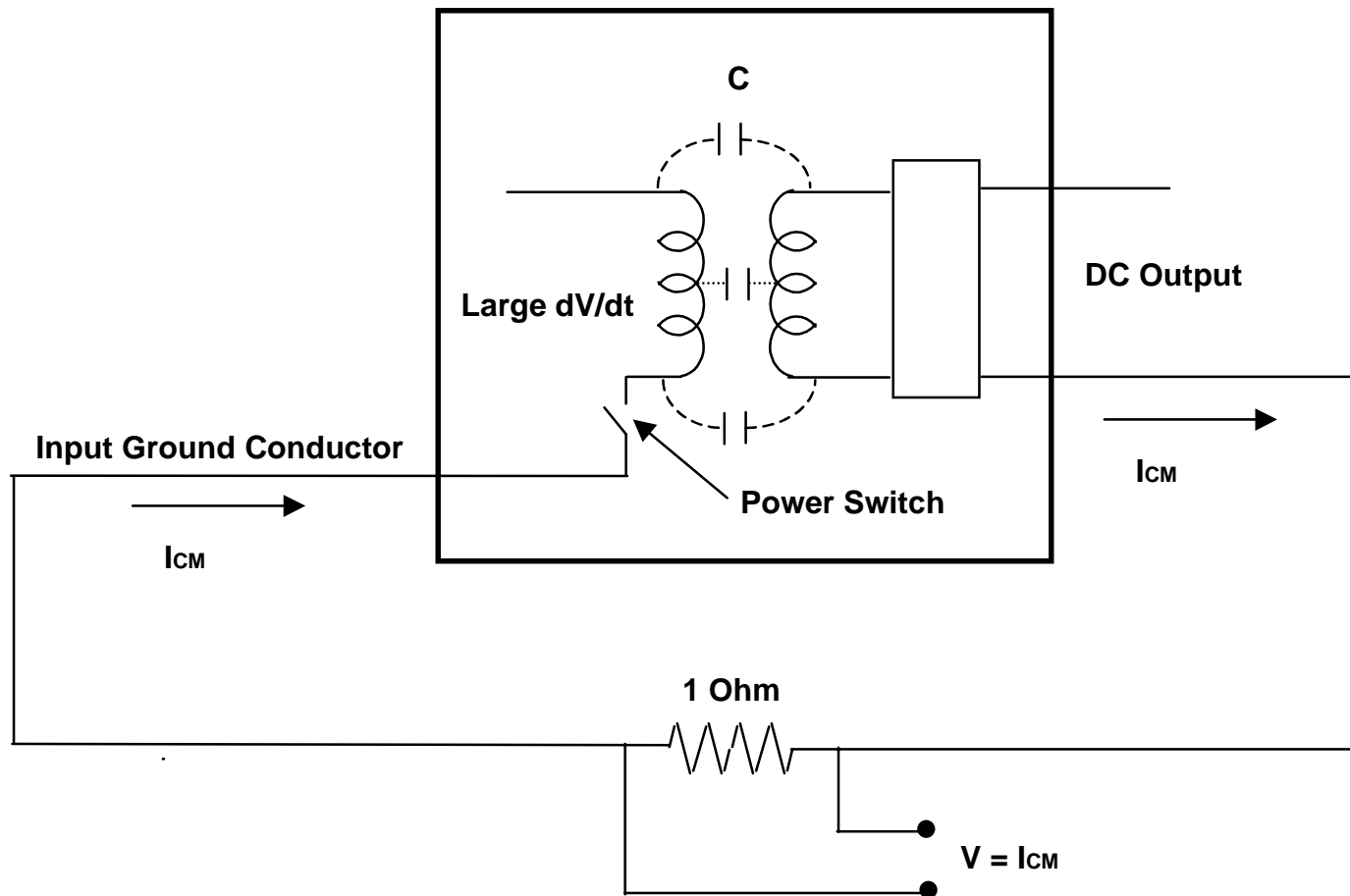
# MINIMIZE PARASITICS



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



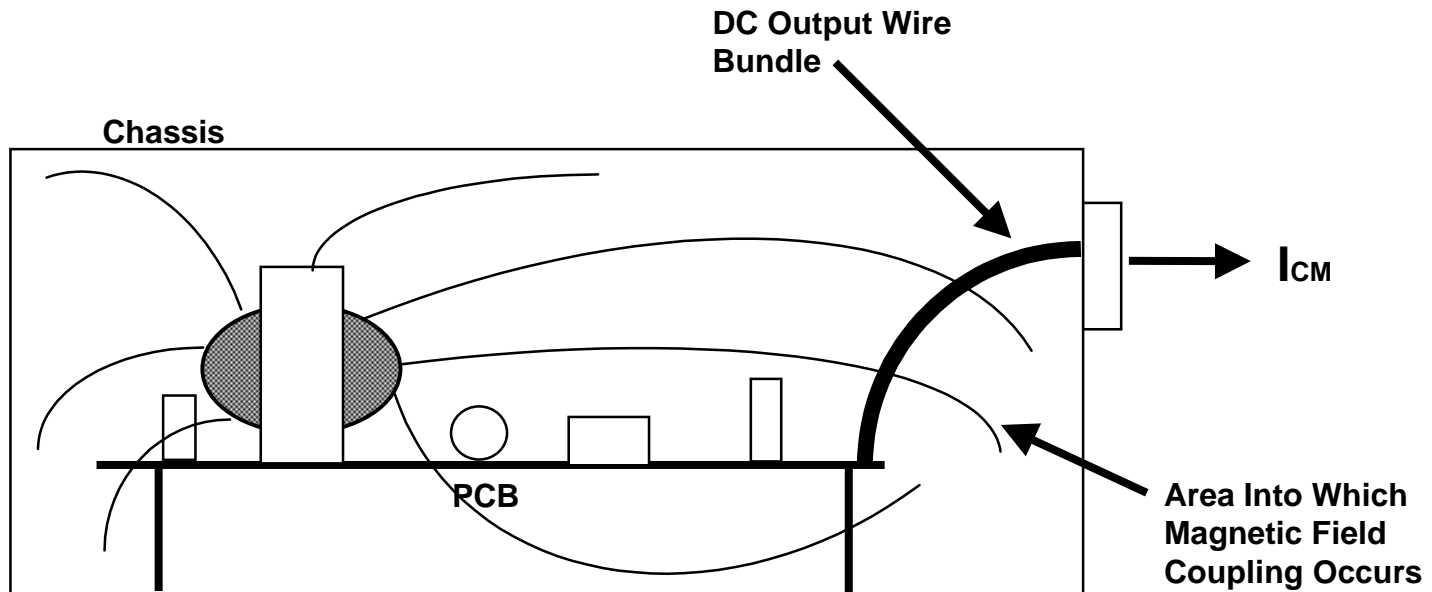
# MEASURING THE COMMON-MODE CURRENT BETWEEN INPUT & OUTPUT A SWITCHING POWER SUPPLY



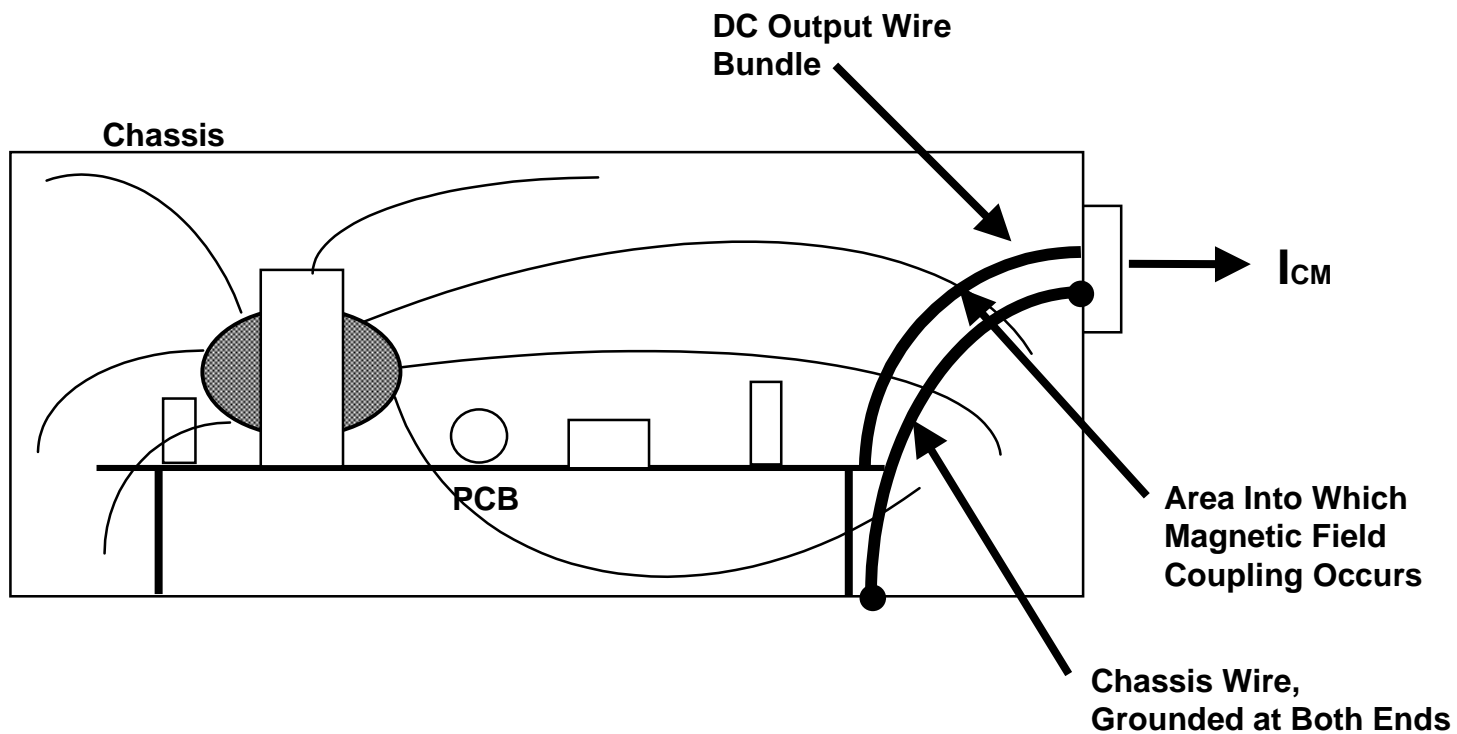
## **DEALING WITH COMMON-MODE NOISE BETWEEN INPUT & OUTPUT OF A SWITCHING POWER SUPPLY**

- **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**

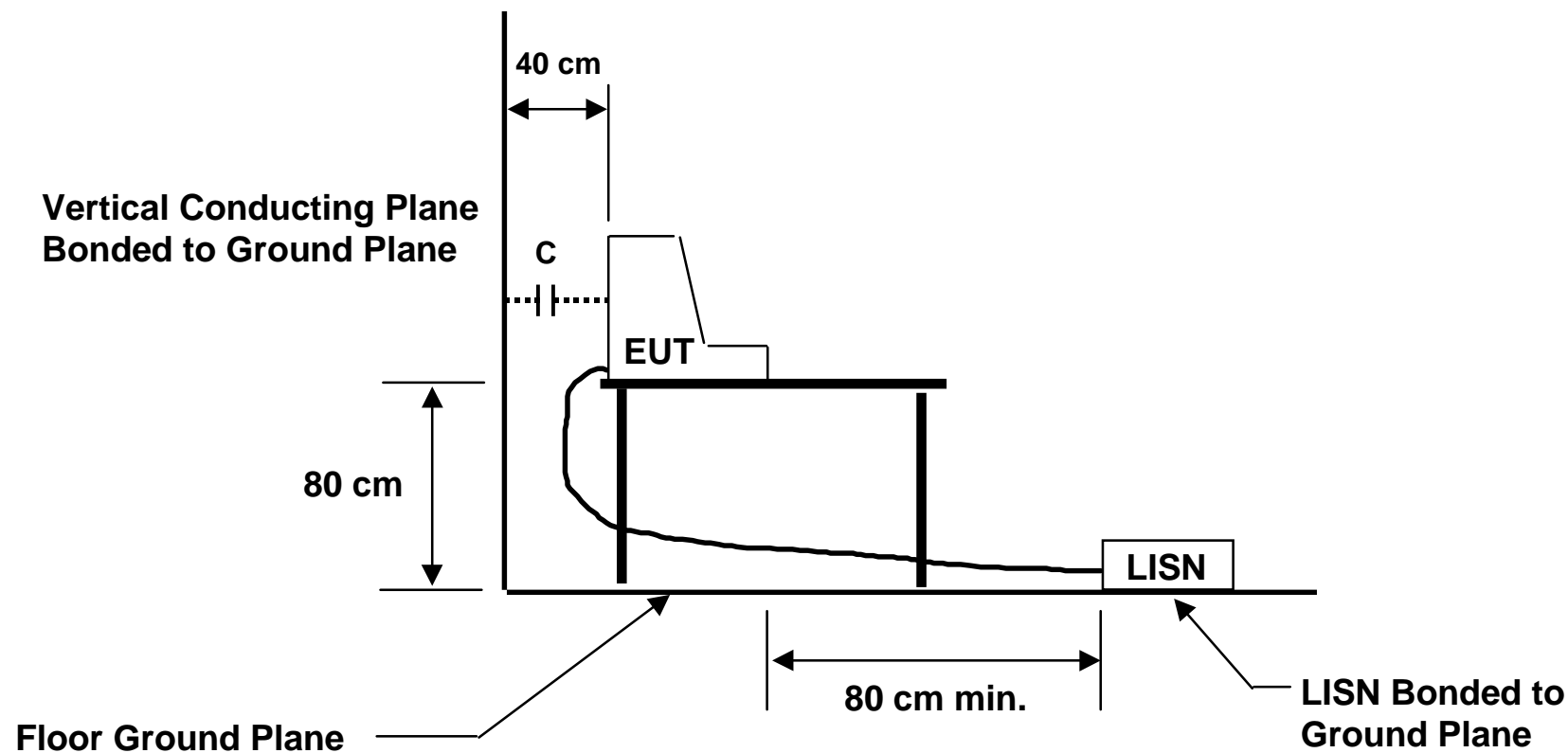
# MAGNETIC FIELD COUPLING TO OUTPUT WIRES



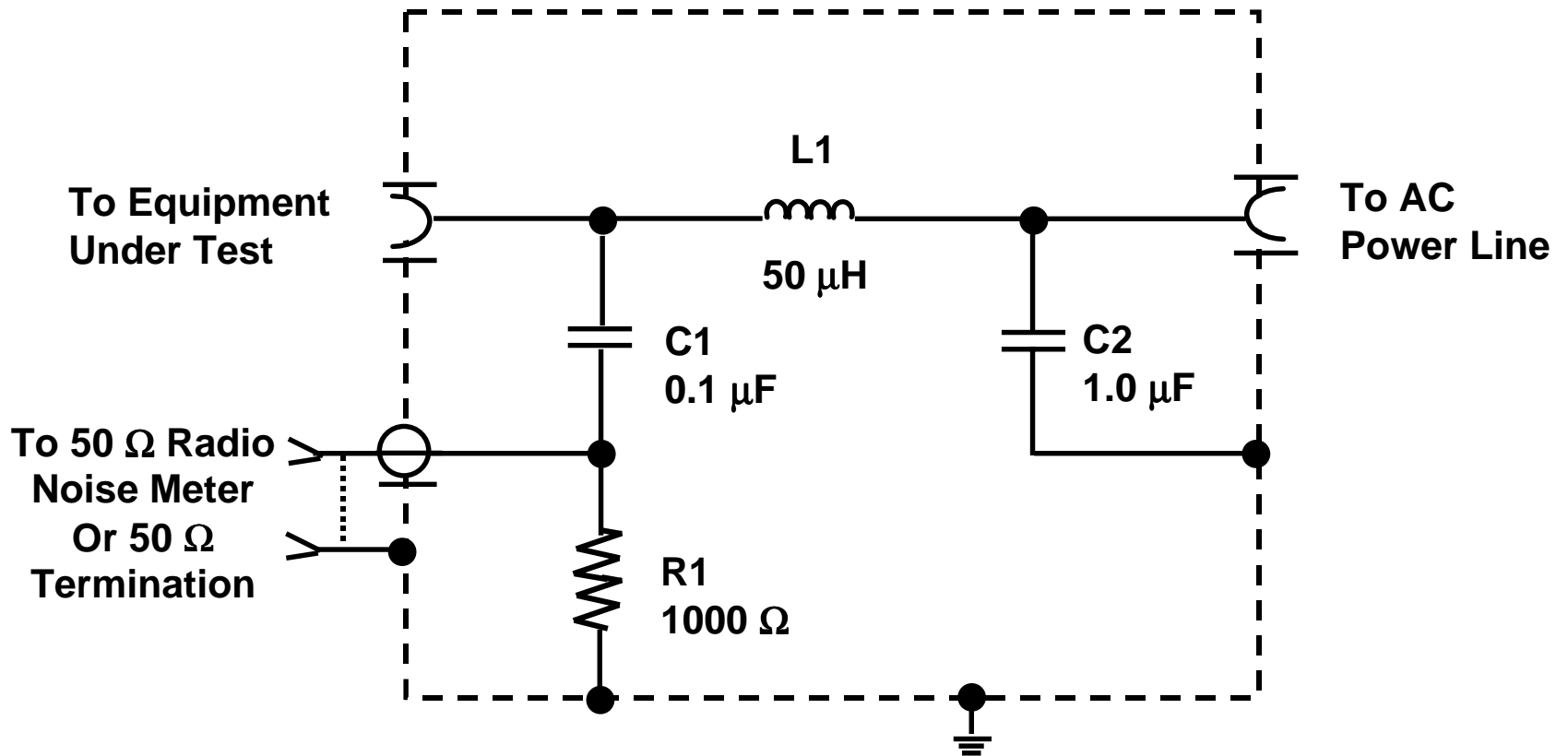
# THE CHASSIS WIRE CONCEPT



# CONDUCTED EMISSION TEST SET-UP



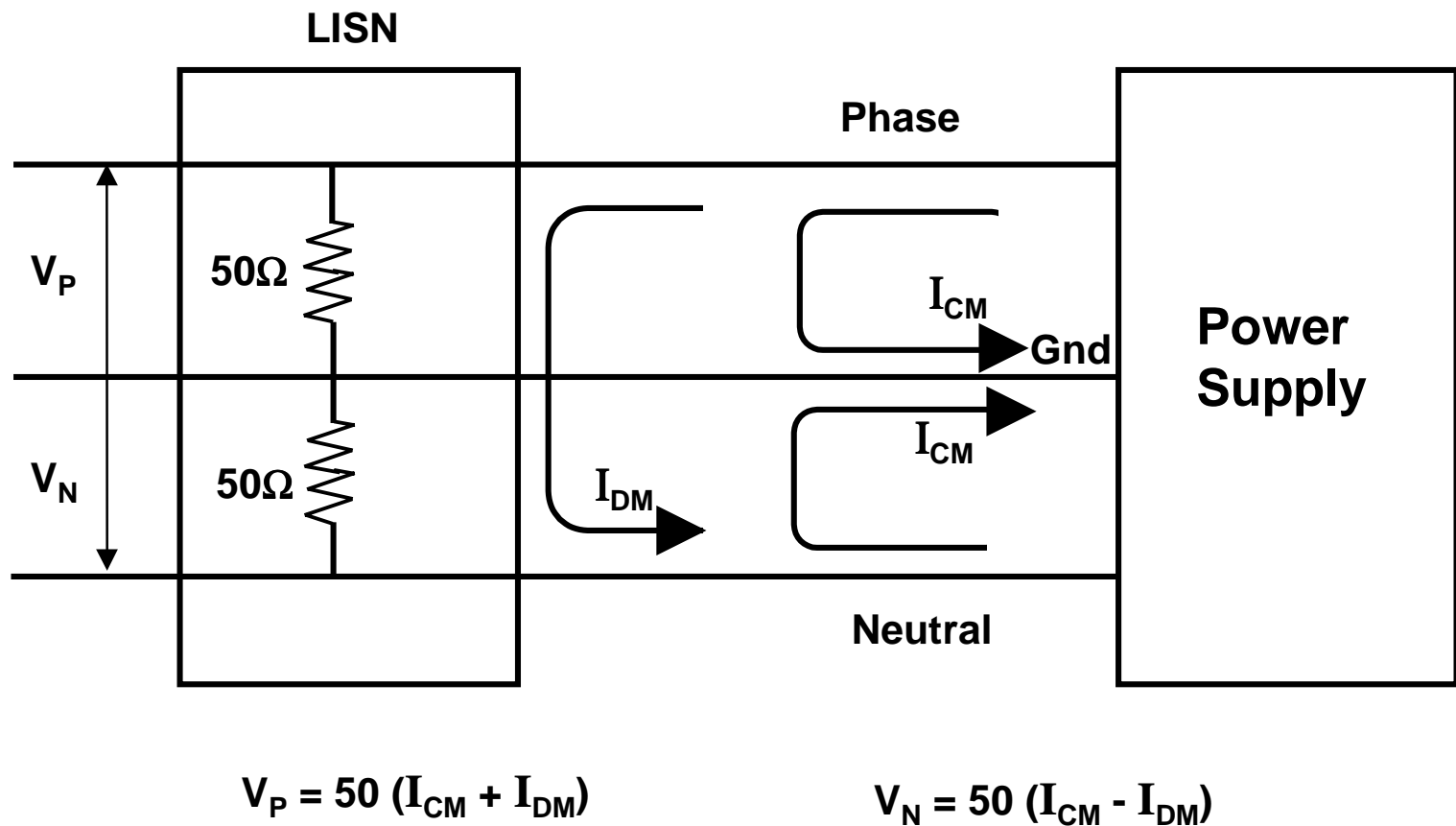
## 50 $\mu\text{H}$ LISN SPECIFIED BY THE FCC



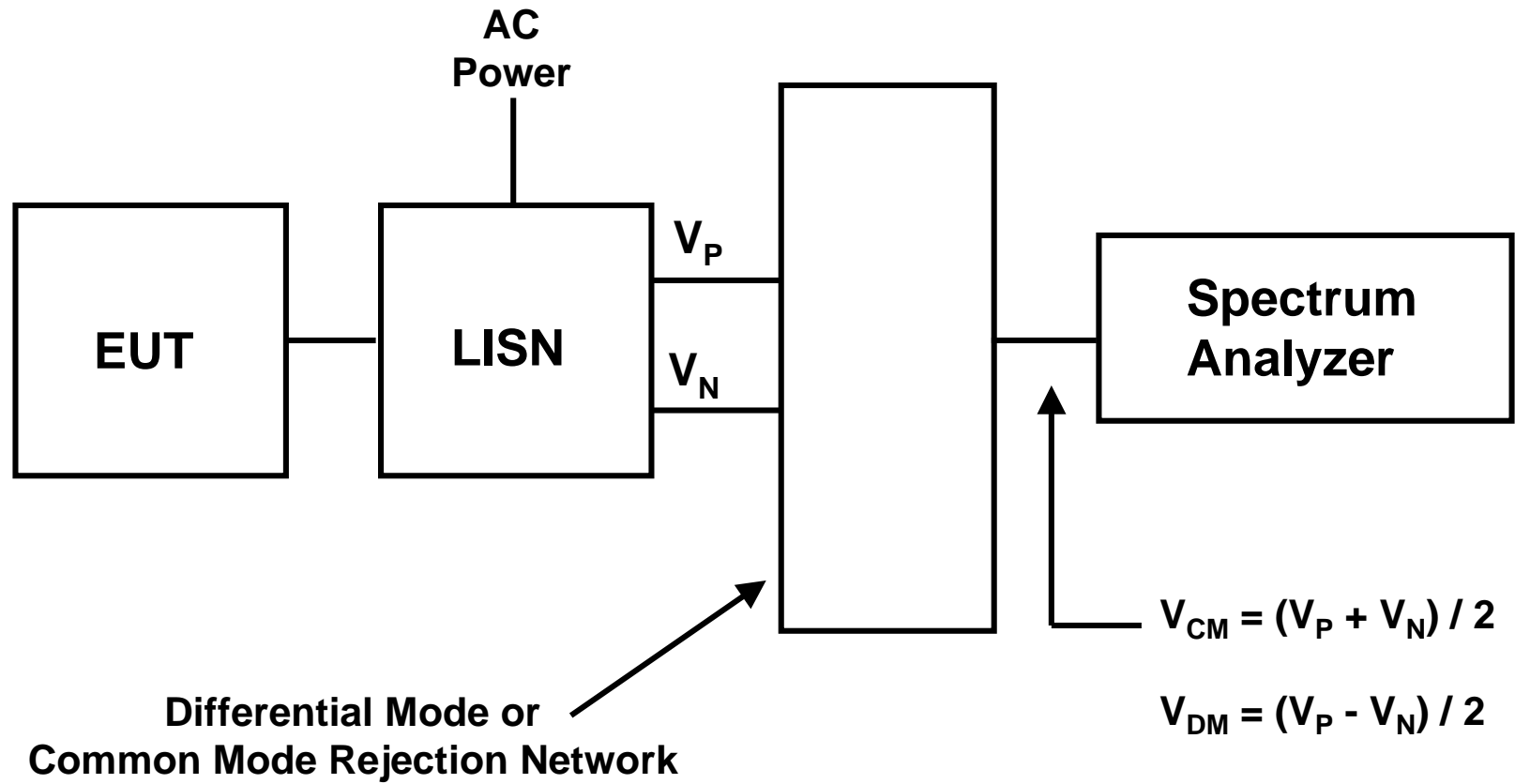
## **TROUBLESHOOTING CONDUCTED EMISSION**

- **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**

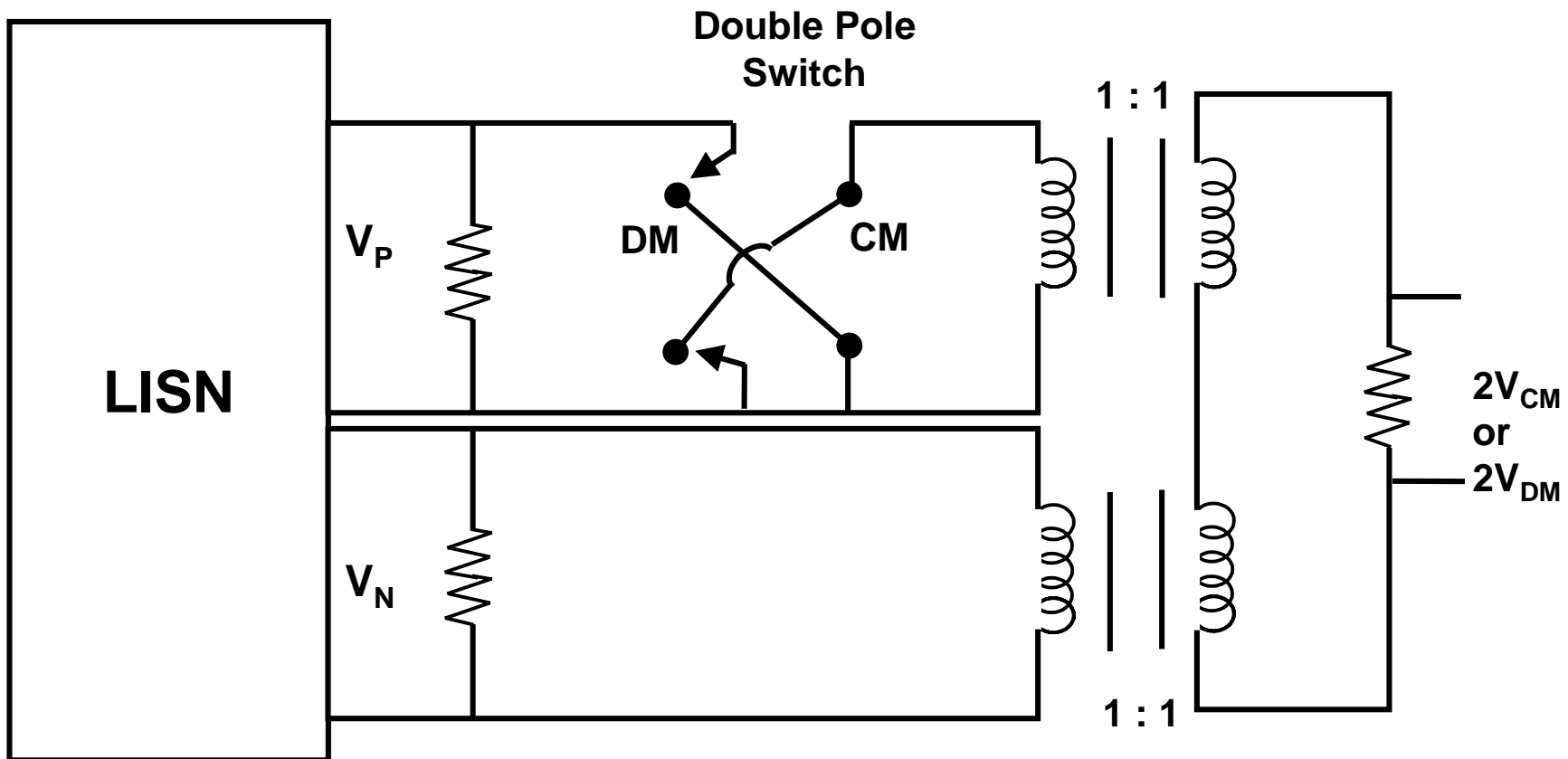
# TOPOLOGY OF CONDUCTED EMISSION



# SEPARATING DIFFERENTIAL MODE AND COMMON MODE EMISSIONS

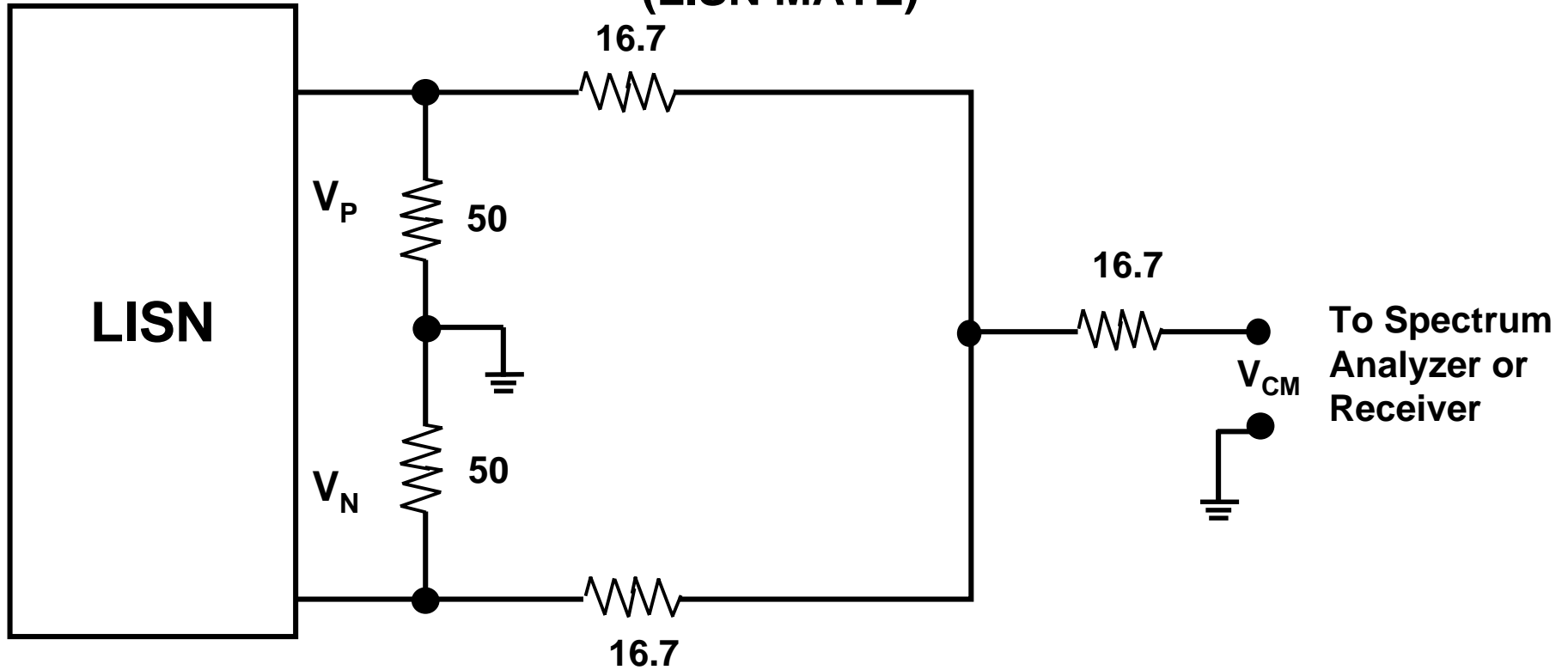


# SEPARATION OF COMMON MODE AND DIFFERENTIAL MODE NOISE VOLTAGES



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

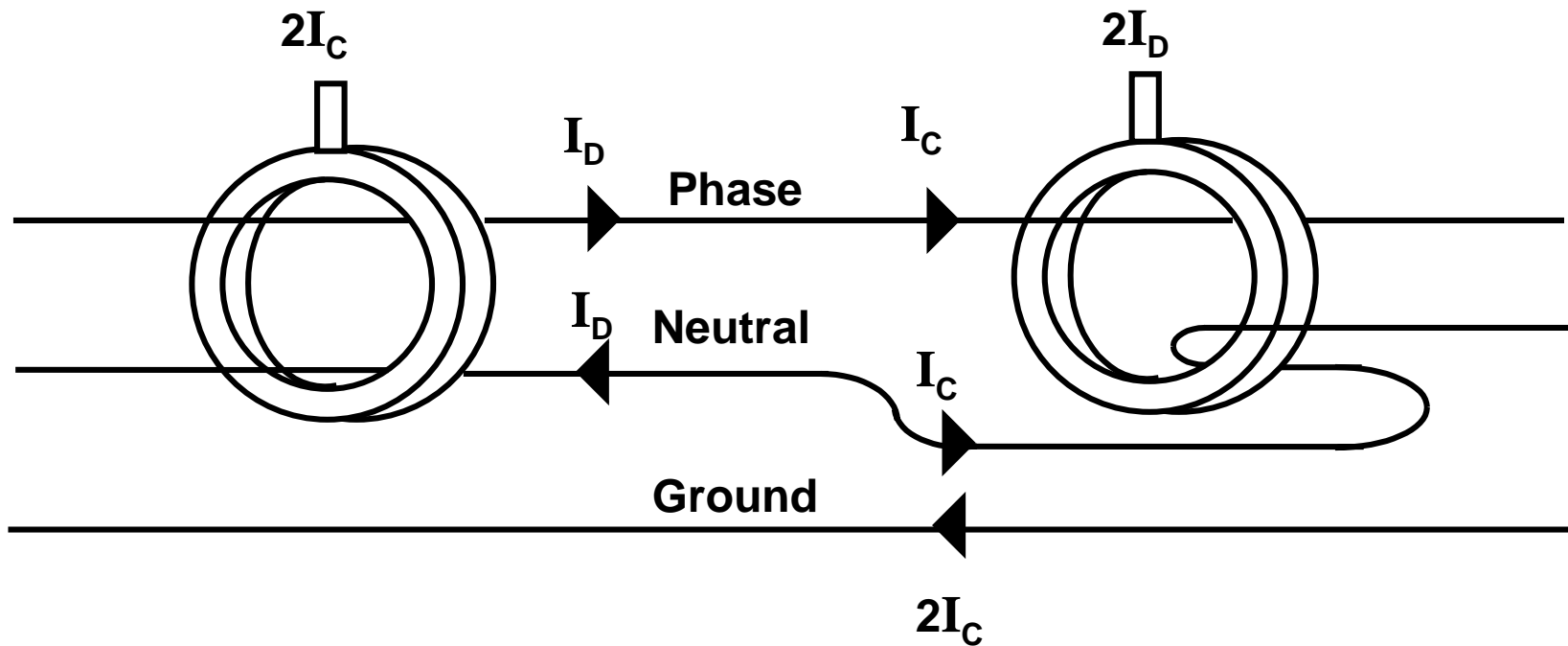
## DIFFERENTIAL MODE REJECTION NETWORK (LISN MATE)



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