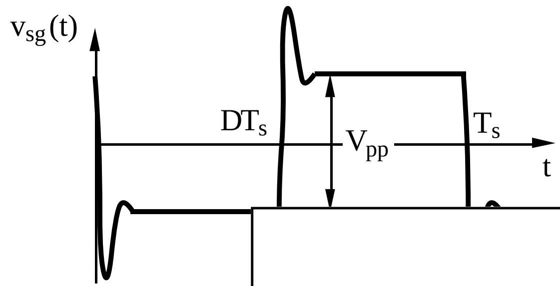
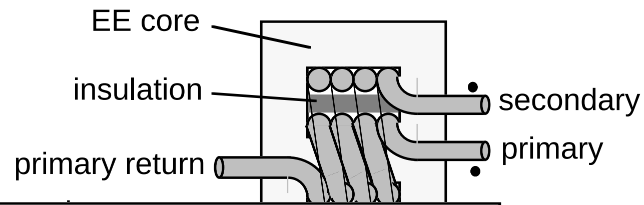
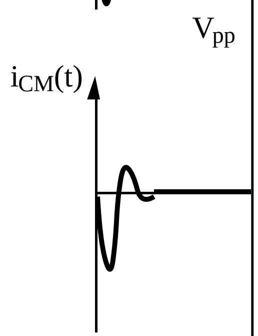


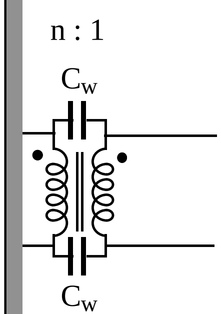


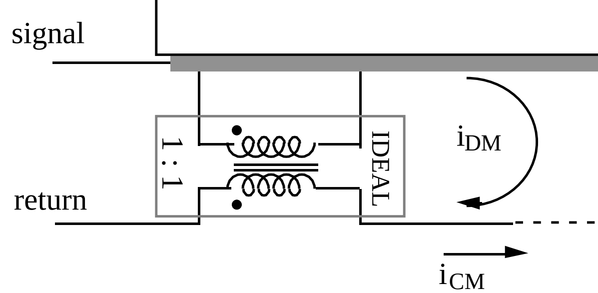
Appendix 4
on

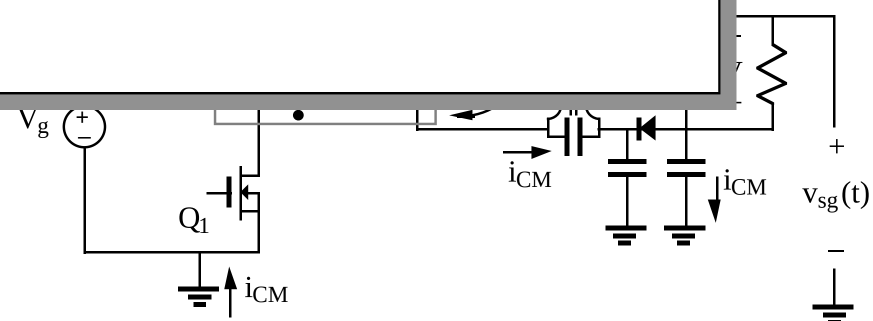
EMI and Layout Fundamentals for Switched-Mode Circuits

R.W. Erickson









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EMI and Layout Fundamentals for Switched-Mode Circuits

R.W. Erickson

- **Introduction**
- **Idealizing assumptions made in beginning circuits**
- **Inductance of wires**
- **Coupling of signals via impedance of ground connections**
- **Parasitic capacitances**
- **The common mode**
- **Common-mode and differential-mode filters**

Introduction

EMI (Electromagnetic Interference) is the unwanted coupling of signals from one circuit or system to another

Conducted EMI: unwanted coupling of signals via conduction through parasitic impedances, power and ground connections

Radiated EMI: unwanted coupling of signals via radio transmission

These effects usually arise from poor circuit layout and unmodeled parasitic impedances

Analog circuits rarely work correctly unless engineering effort is expended to solve EMI and layout problems

Sooner or later (or now!), the engineer needs to learn to deal with EMI

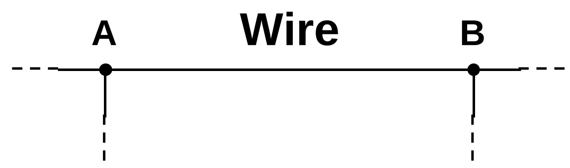
The ideal engineering approach:

- **figure out what are the significant EMI sources**
- **figure out where the EMI is going**
- **engineer the circuit layout to mitigate EMI problems**

Build a layout that can be understood and analyzed

Assumptions made in Circuits 101

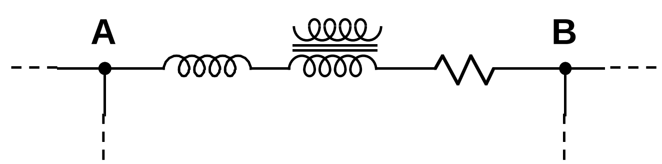
1. Wires are perfect (equipotential) conductors



$$V_A = V_B$$

This assumption ignores

- **wire resistance**
- **wire inductance**
- **mutual inductance with other conductors**



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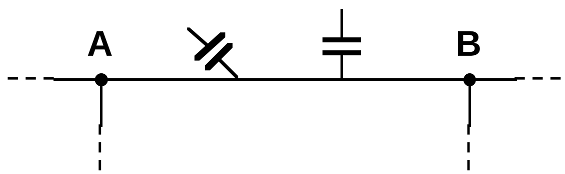
A related assumption:

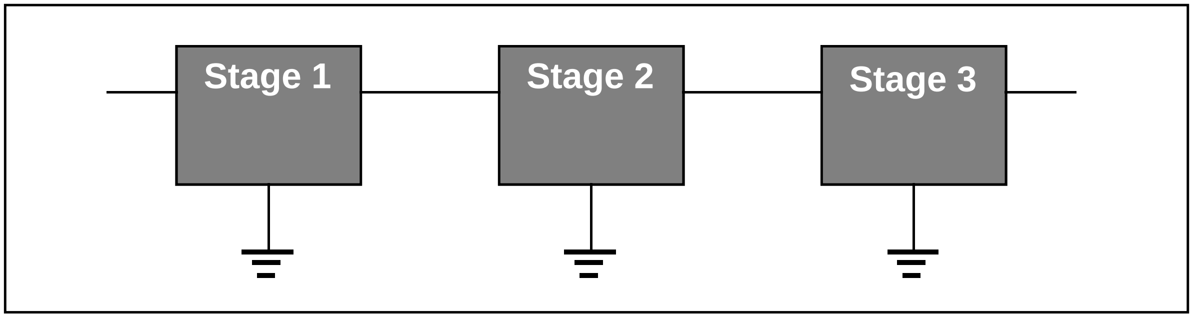
1a. The space surrounding a wire is a perfect insulator (dielectric constant = 0)

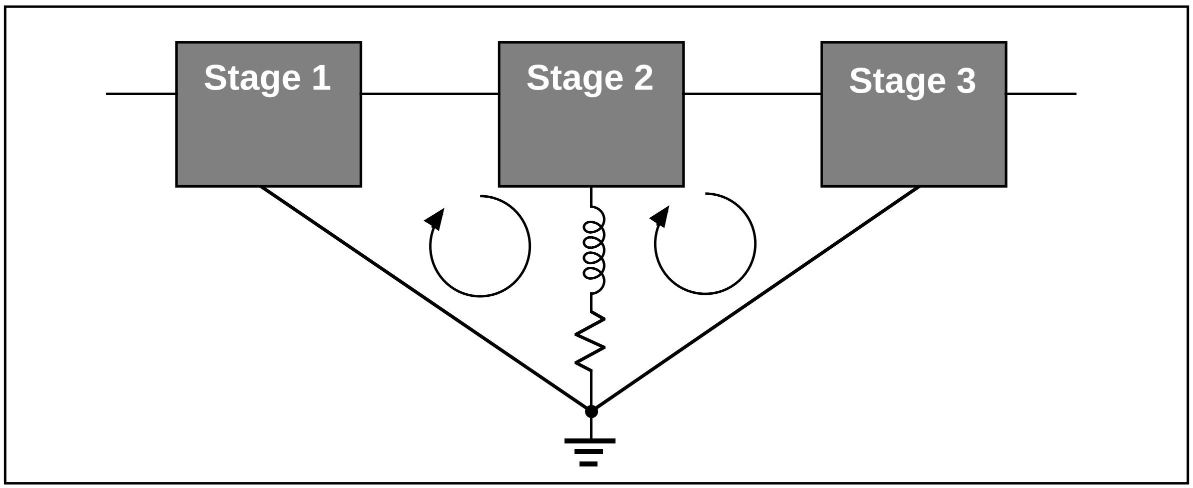
This assumption ignores capacitance between conductors



2. The ground (reference) node is at zero potential

Formally, this is a definition. But there is an implicit assumption that all parts of the system can be connected via ideal conductors to a common ground node. In practice, it is often quite difficult to ensure that each stage of a system operates with the same zero potential reference.





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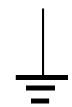
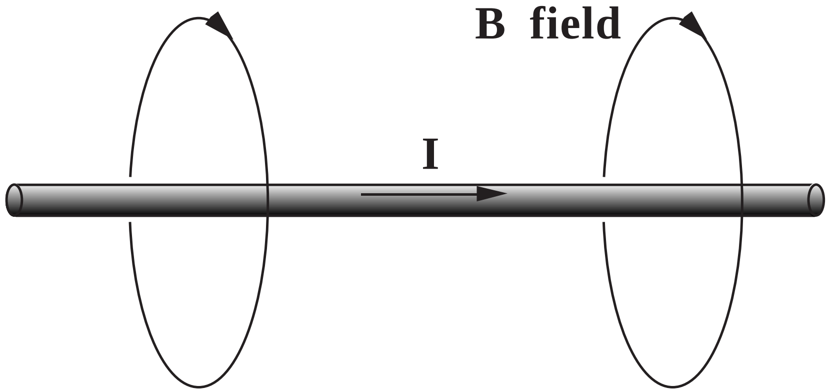
We reinforce the problem by freely using the ground symbol



By use of this symbol, we avoid indicating how the actual wiring connection is made. In consequence, the possibility of conducted EMI via nonideal ground conductors is ignored

About inductance of wires

Single wire in space



Self inductance

$$L = \frac{\lambda}{i}$$

$$L = 0.00508\, l \left(2.303 \log_{10}\left(\frac{4l}{d}\right) - 0.75\right) \mu H$$

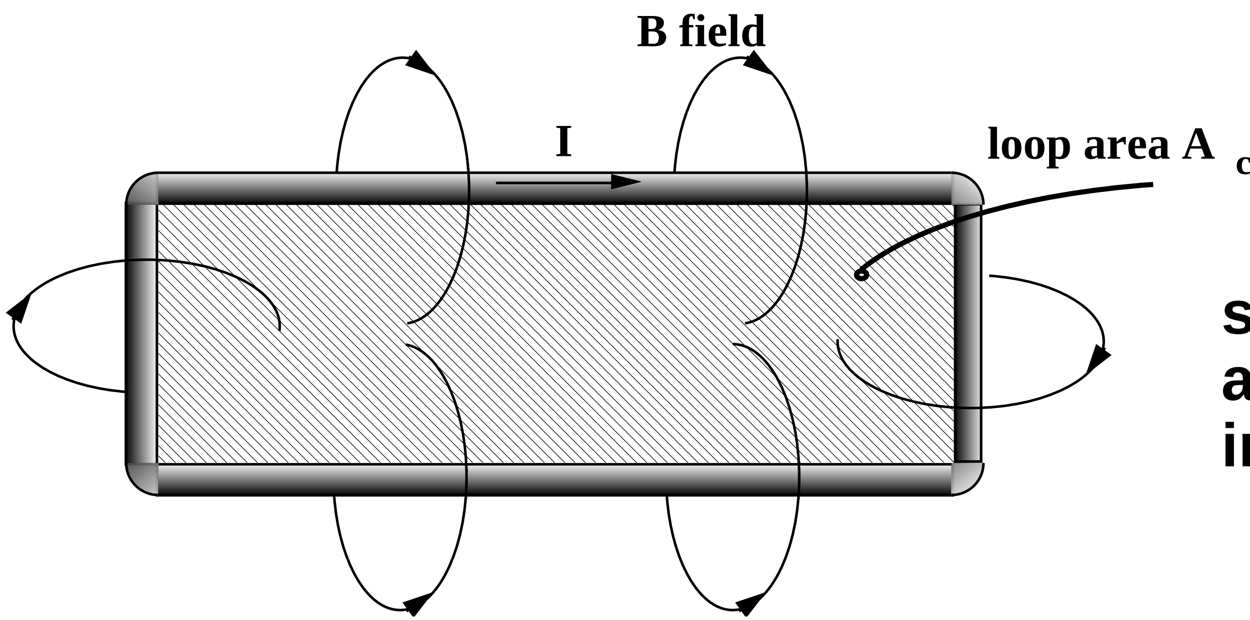
Terman, *Radio Engineer's Handbook*, p. 48ff, 1943

l = **wire length**
d = **wire diameter**
dimensions in inches

- **Larger wire has lower inductance, because B-field must take longer path length around wire**
- **But how does the charge get back from end to beginning ? There is no closed loop, and so formula ignores area of loop**
- **Formula ignores effects of nearby conductors**

A more realistic scenario:

current flows around a closed loop



single-turn air-core inductor

Simple-minded inductance formula:

$$L = \frac{\mu_o A_C}{l_m}$$

$\mu_o = 4\pi \cdot 10^{-7}$ **H/m**

l_m = **effective magnetic path length**

To reduce inductance: reduce loop cross-sectional area (by routing of wires), or increase path length (use larger wire).

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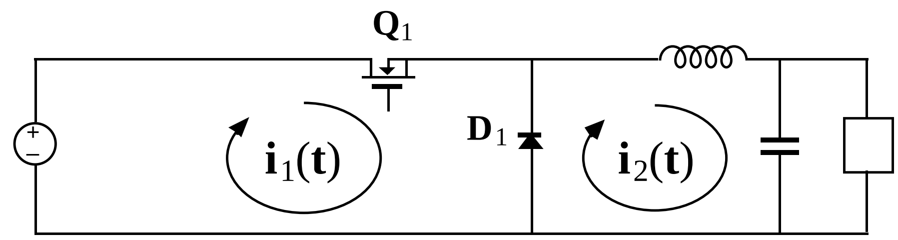
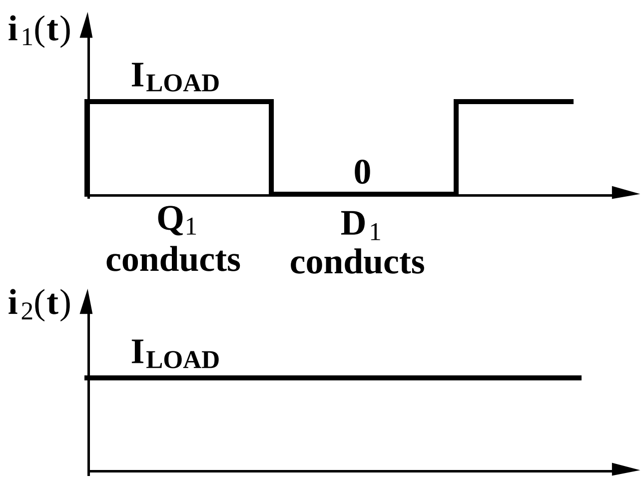
Example: Buck converter

Use loop analysis





switched input current $i_1(t)$ contains large high frequency harmonics

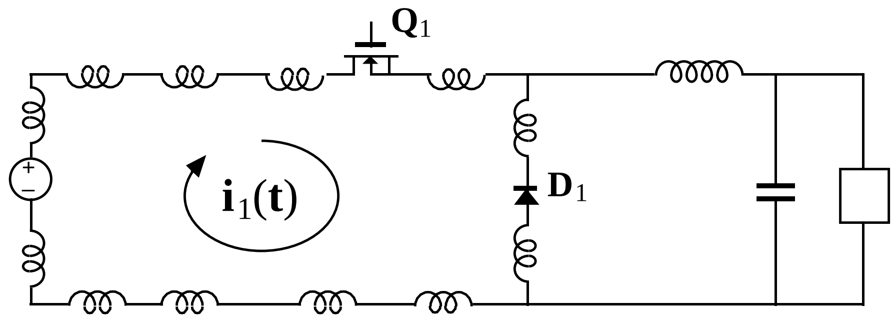
—hence inductance of input loop is critical

inductance causes ringing, voltage spikes, switching loss, generation of B- and E-fields, radiated EMI

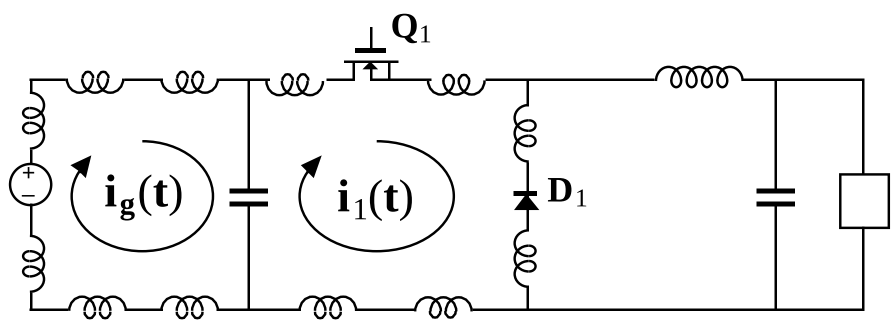
the second loop contains a filter inductor, and hence its current $i_2(t)$ is nearly dc

—hence additional inductance is not a significant problem in the second loop

Parasitic inductances of input loop explicitly shown:

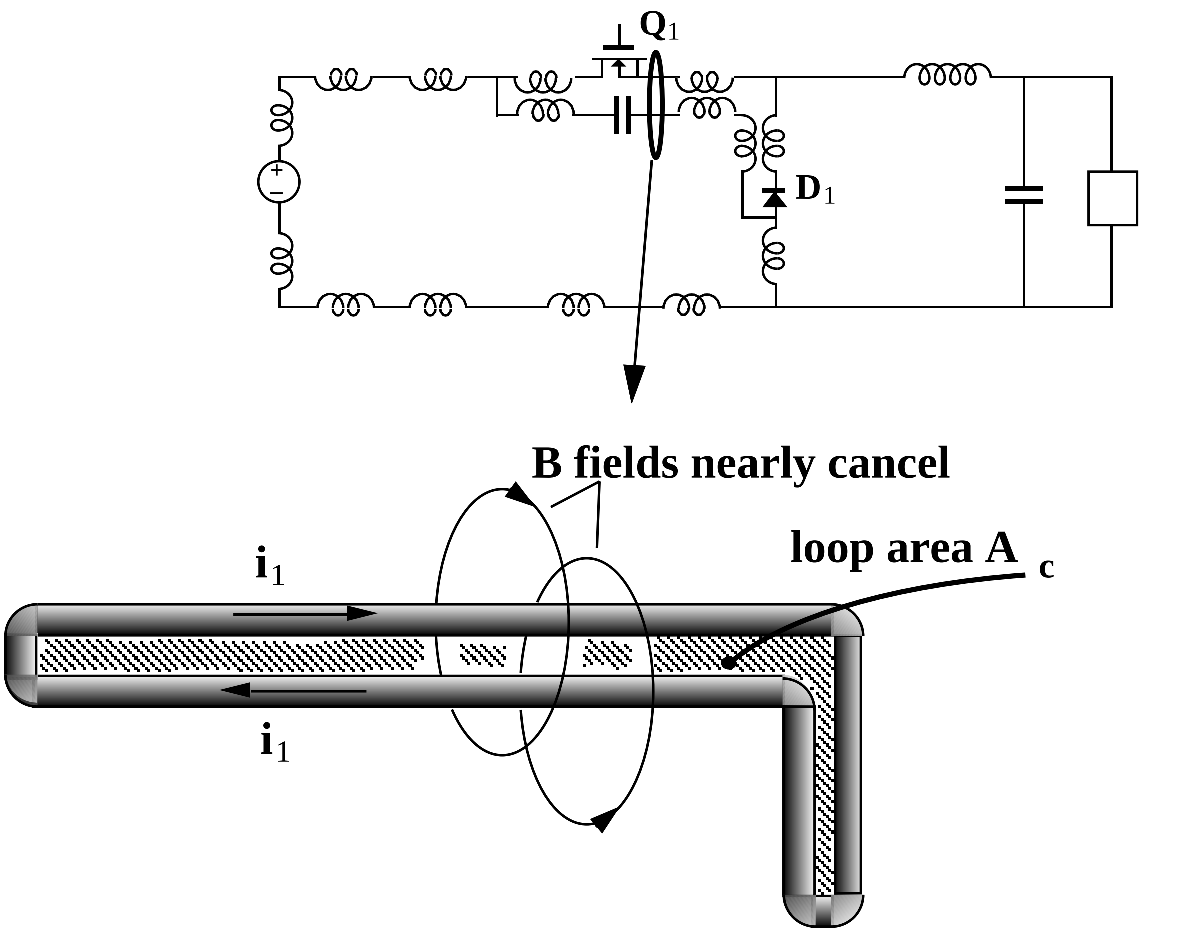


Addition of bypass capacitor confines the pulsating current to a smaller loop:



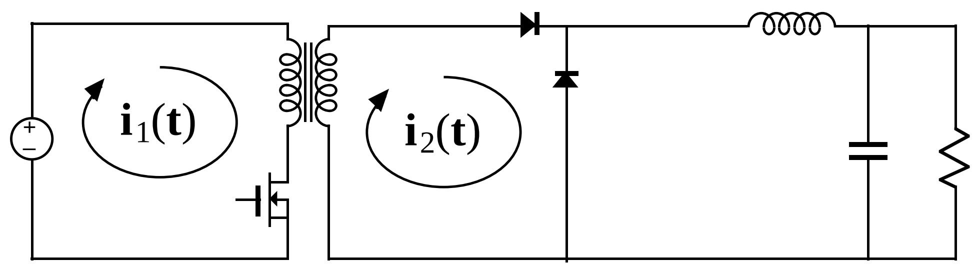
high frequency currents are shunted through capacitor instead of input source

Even better: minimize area of the high frequency loop, thereby minimizing its inductance

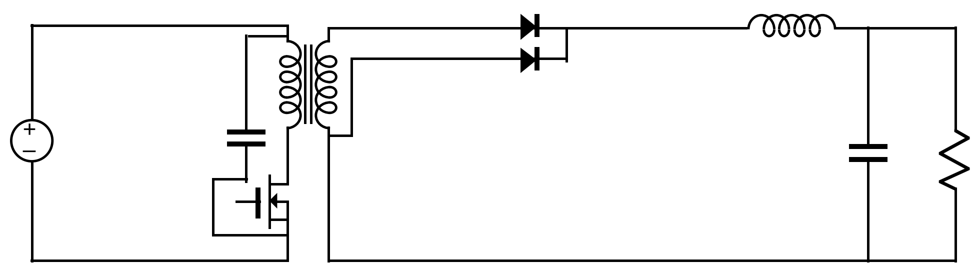


Forward converter

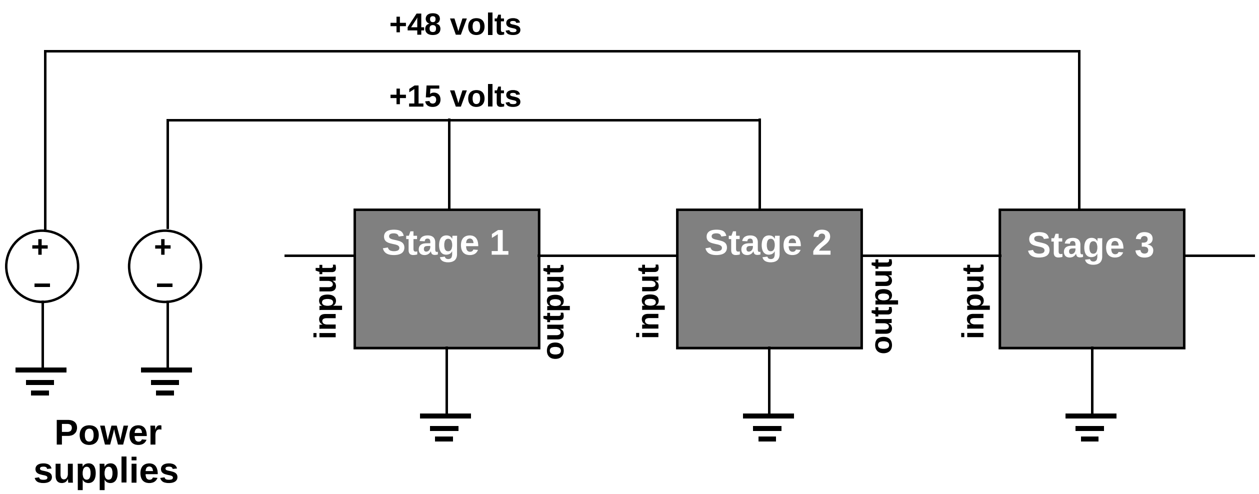
Two critical loops:



Solution:

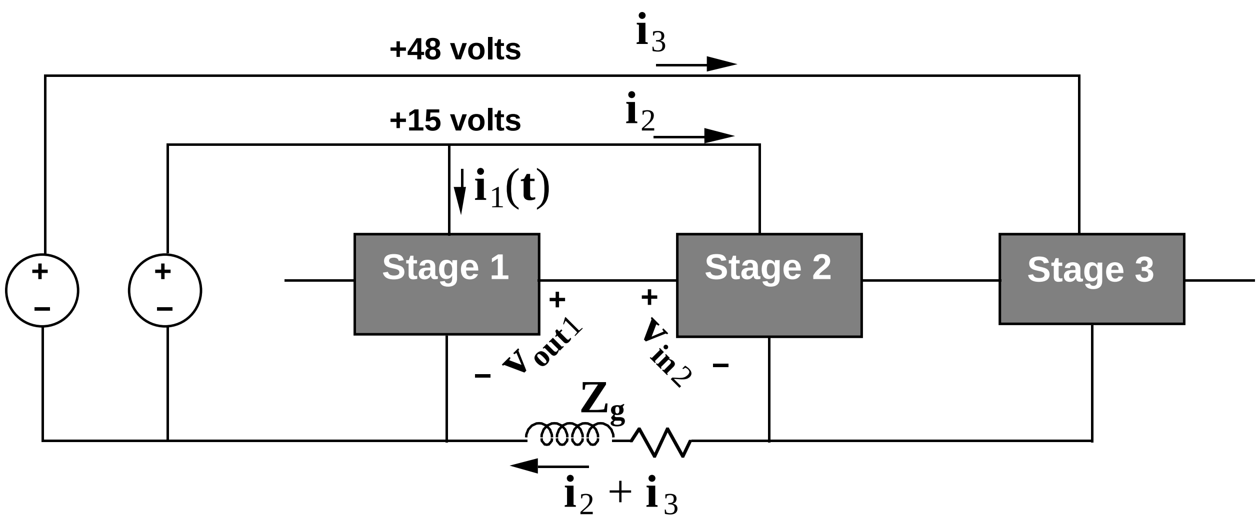


Unwanted coupling of signals via impedance of ground connections



- **All currents must flow in closed paths: determine the entire loop in which large currents flow, including the return connections**
- **Ground (zero potential) references may not be the same for every portion of the system**

Example: suppose the ground connections are

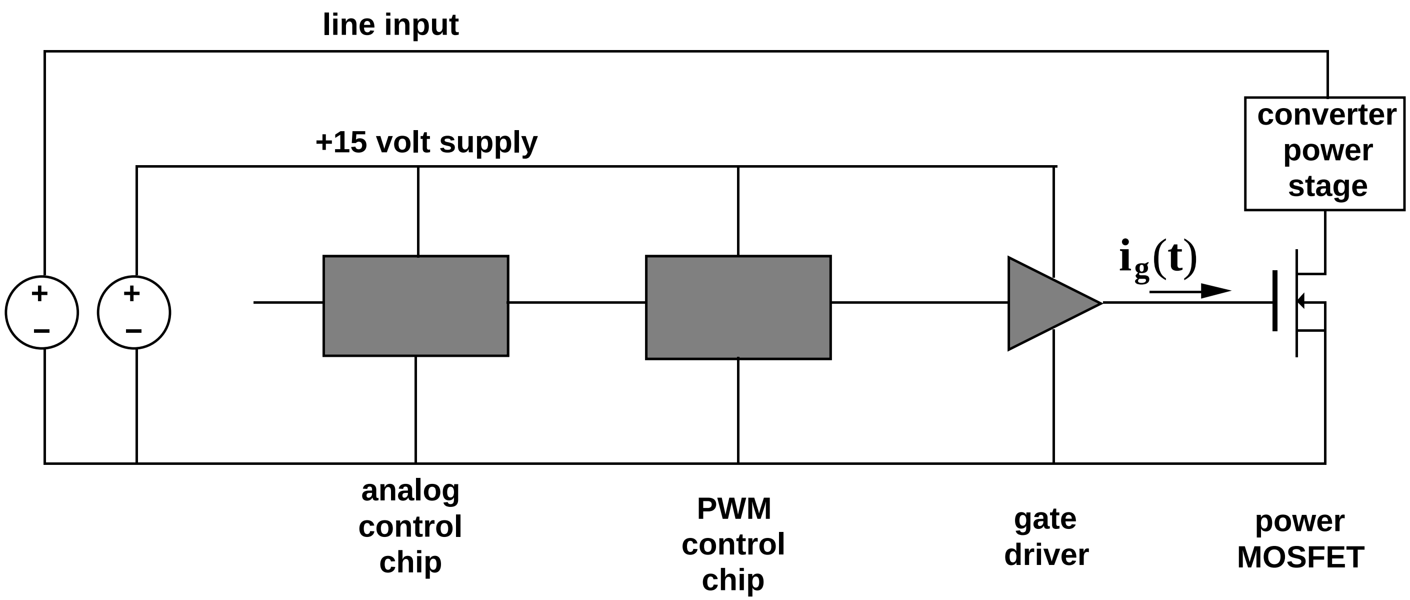


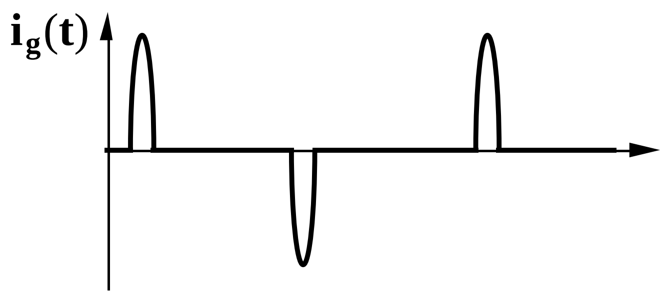
$$v_{in2} = v_{out1} - Z_g\,(i_2 + i_3)$$

“Noise” from stages 2 and 3 couples into the input to stage 2

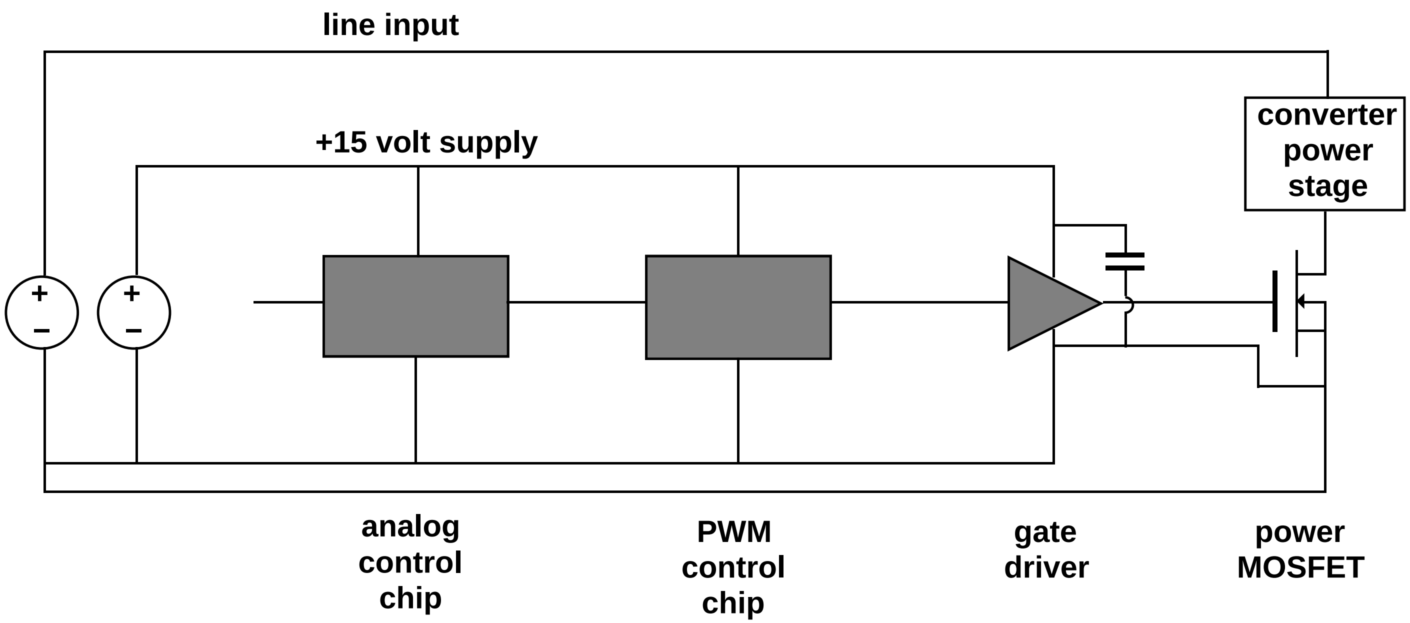
This represents conducted EMI, or specifically corruption of the ground reference by system currents

Example: gate driver





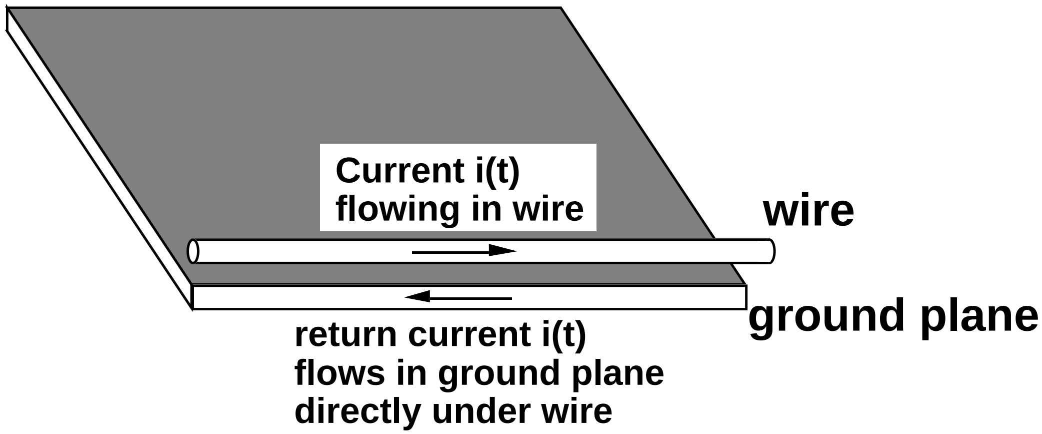
Solution: bypass capacitor and close coupling of gate and return leads



High frequency components of gate drive current are confined to a small loop

A dc component of current is still drawn output of 15V supply, and flows past the control chips. Hence, return conductor size must be sufficiently large

About ground planes



Inductance of return connections is minimized

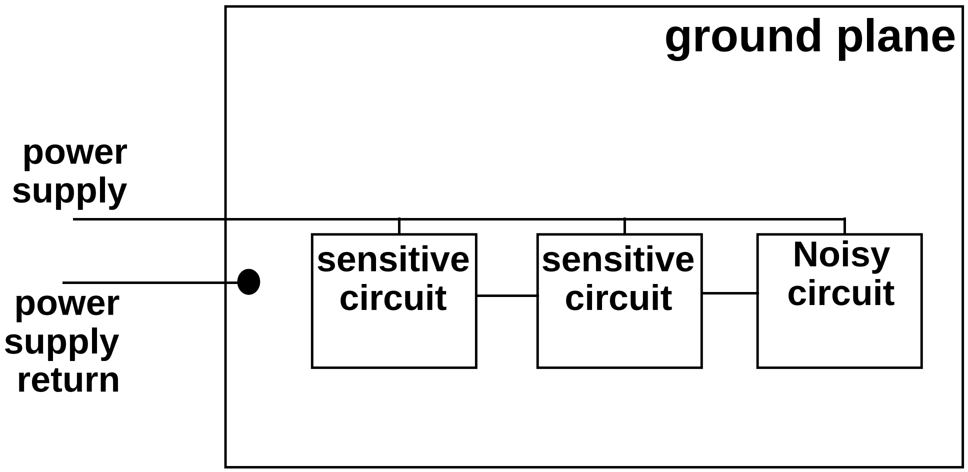
Hence ground planes tend to exhibit lower impedance ground connections, and more nearly equipotential ground references

Ground planes are especially effective in the analog control portions of switching regulator circuits

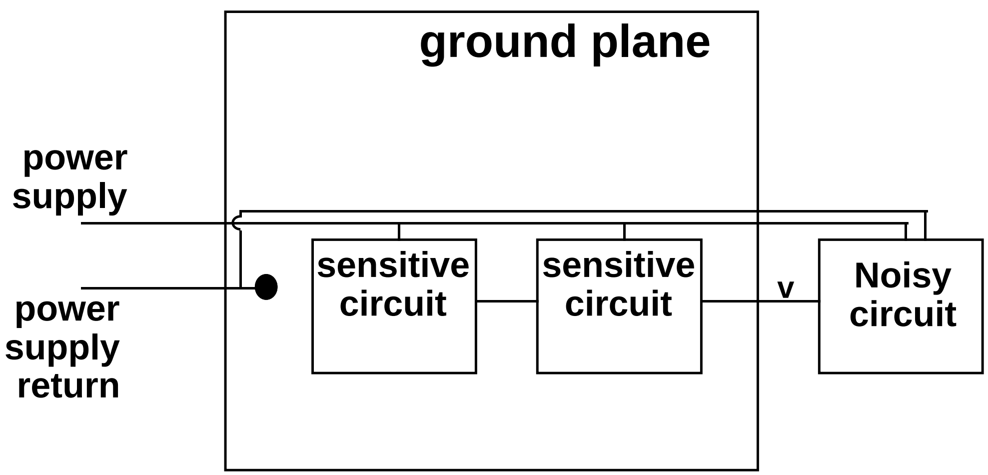
But it is still possible to observe significant coupling of noise in ground, by

- **poor layout of ground plane, or**
- **high resistance of ground plane**

A poor ground plane layout



Return current of noisy circuit runs underneath sensitive circuits, and can still corrupt their ground references

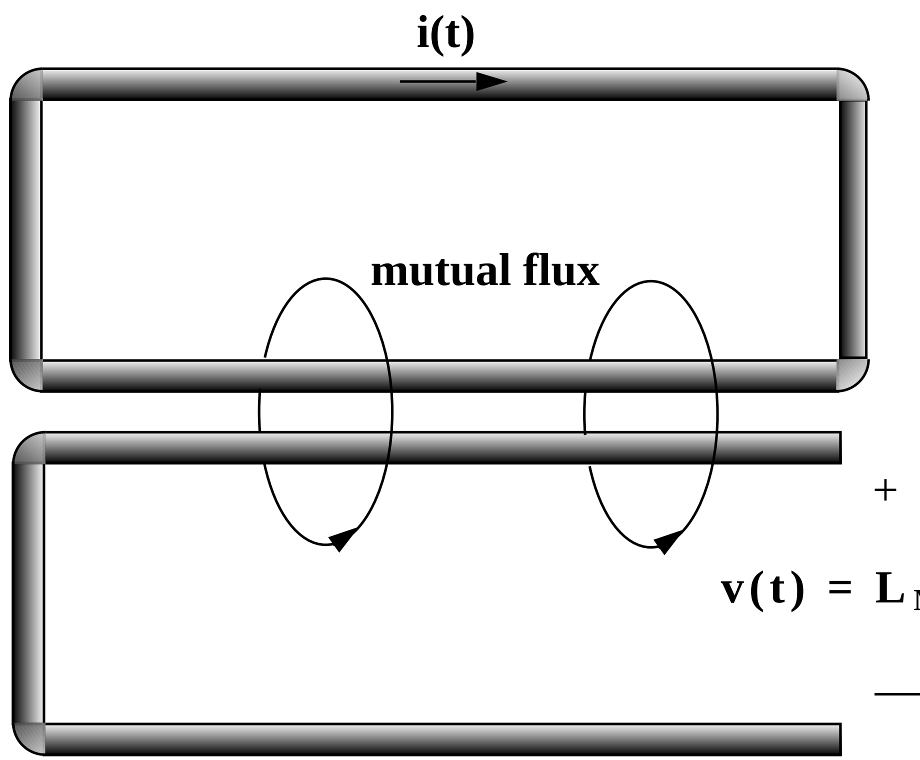


A solution is to remove the noisy circuit from the ground plane. One could then run a separate ground wire for the noisy circuit. The only drawback is that noise can be coupled into the input signal v.

Coupling of signals via magnetic fields

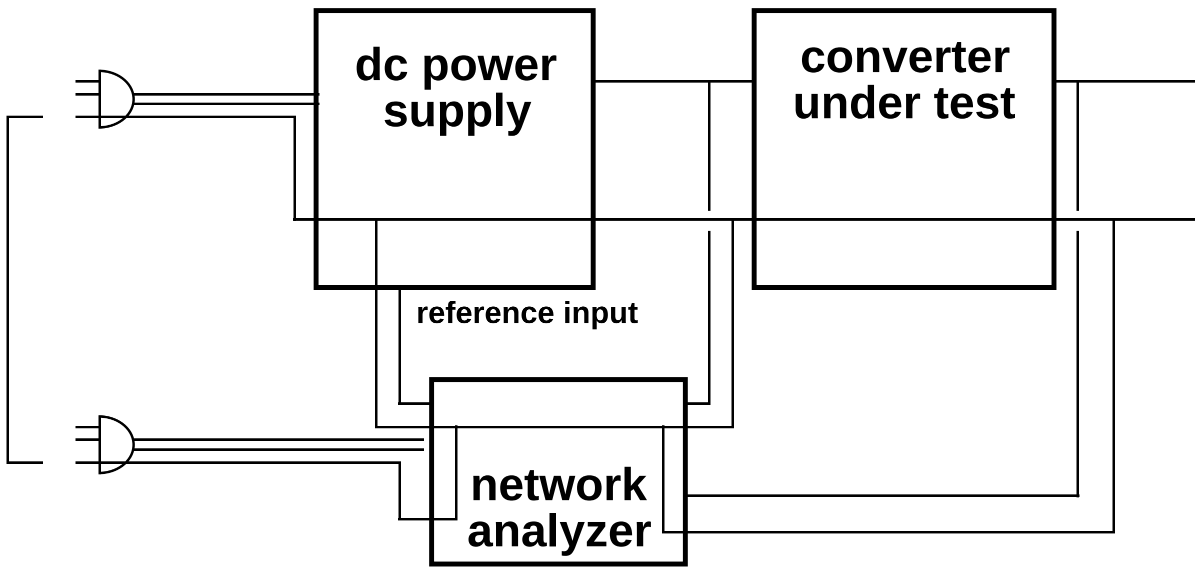
Loop containing ac current i(t) generates B field

which links another conductor, inducing an unwanted voltage v(t)



$$v(t) = L_M \frac{di(t)}{dt}$$

This phenomenon can sometimes be a problem when ground loops are present. Circulating ground currents are then induced, which lead to variations in the ground reference potential



Measurement of audiosusceptibility: observed unusual and unexpected results

Fixed by breaking ground loops

Audiosusceptibility then was as expected

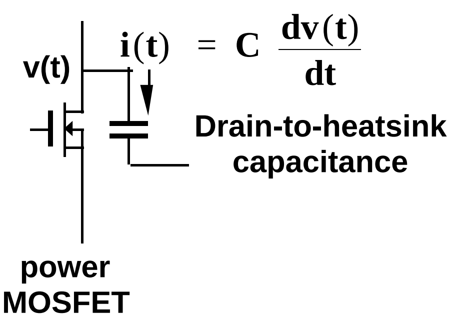
Stray capacitances

Most significant at high voltage points in circuit

Two major sources of EMI:

- **Transformer interwinding capacitance**
- **MOSFET drain-to-heatsink capacitance**

Drain-to-heatsink capacitance



When the switched drain voltage is applied to this capacitance, current spikes must flow.

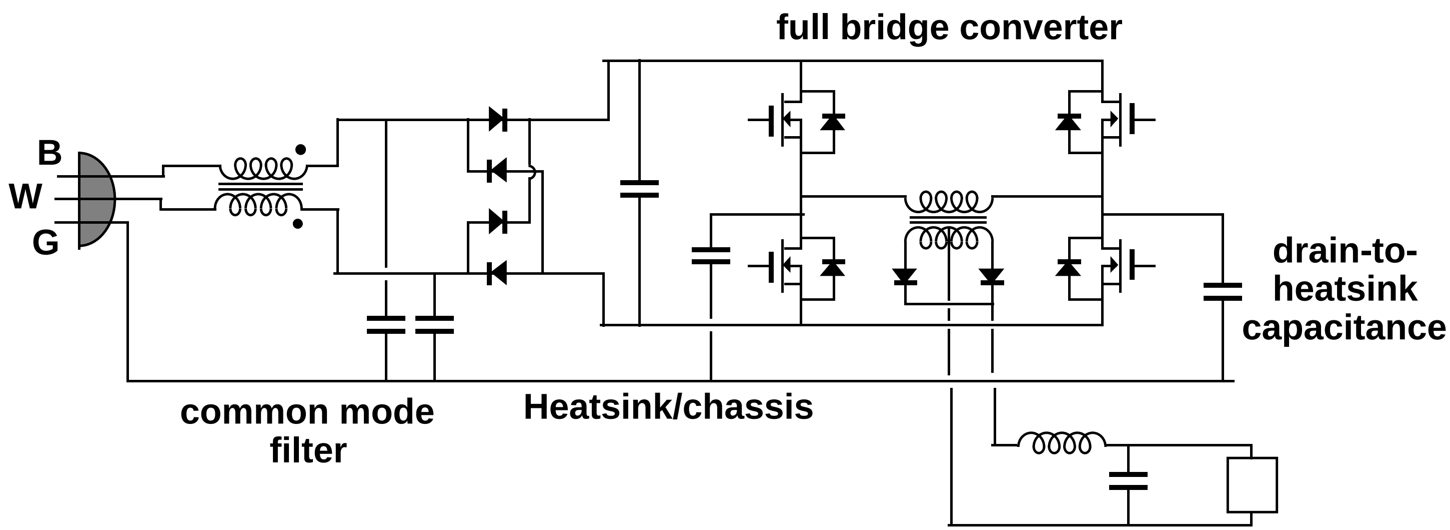
The currents must flow in a closed path (a loop). What is the loop in your circuit?

To control the effects of these currents,

- **provide a short path for them to return to their origin**
- **add common-mode filters**
- **slow down switching times**

Common mode noise generation

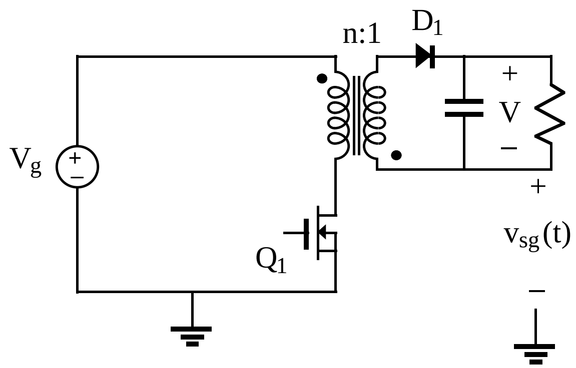
by drain-to-heatsink capacitance



Common mode noise generation

by transformer interwinding capacitance

Flyback converter example



Transformer interwinding capacitance causes currents to flow between the isolated (primary and secondary) sides of the transformer, and can cause the secondary-side ground voltage to switch at high frequency: $v_{sg}(t)$ contains a high-frequency component.

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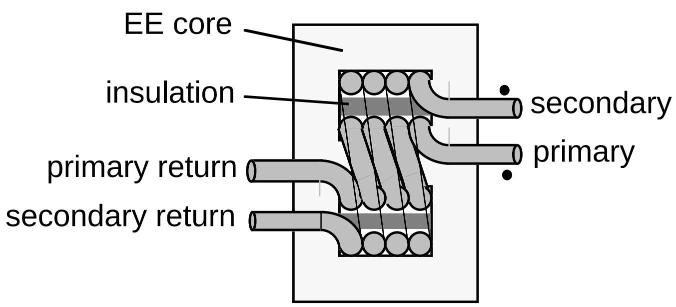
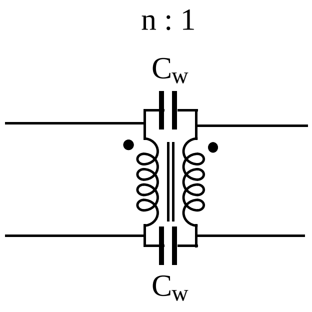
Modeling transformer interwinding capacitance

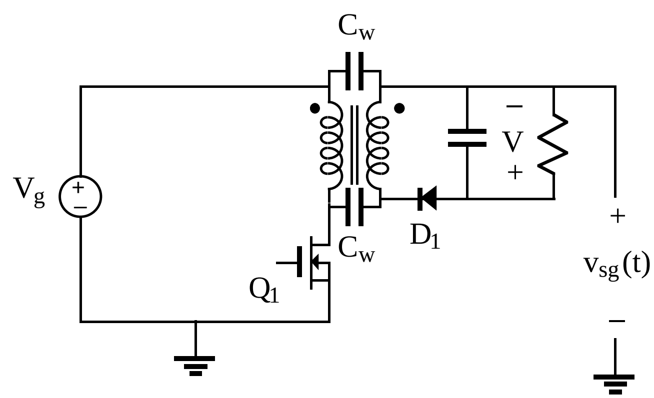
Suppose the transformer is wound as follows:



A simple lumped element model, including interwinding capacitance:

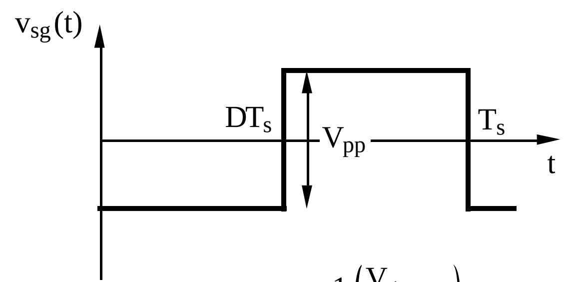


Flyback converter ground potentials



Flyback converter circuit, with interwinding capacitance modeled

One can solve the circuit to find the high-frequency ac component of $v_{sg}(t)$. The result is

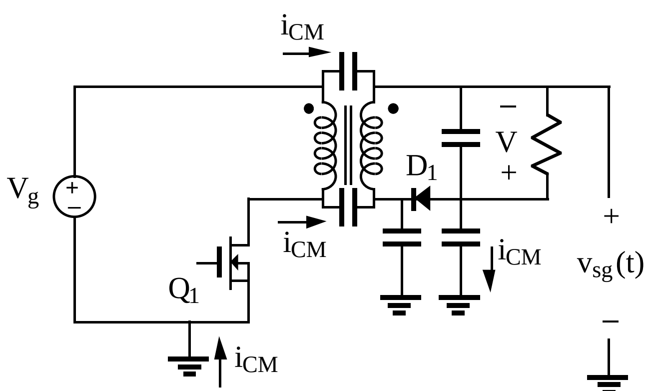


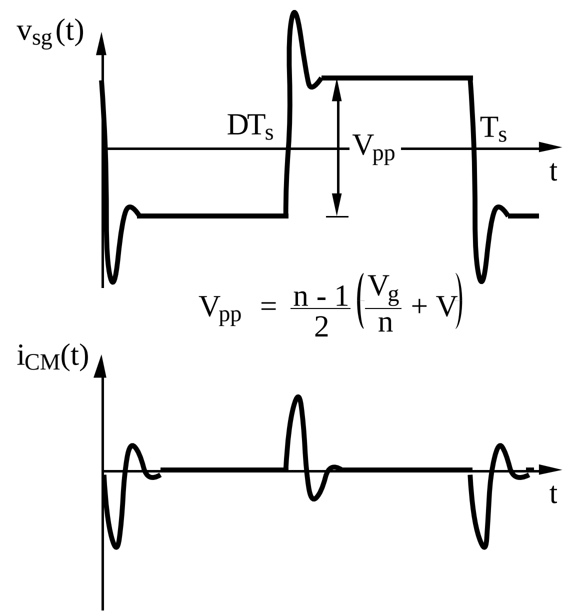
$$V_{pp} = \frac{n-1}{2}\left(\frac{V_g}{n} + V\right)$$

- **The secondary ground potential switches at high frequency with respect to the primary ground.**
- **The peak-peak voltage V_{pp} is typically approximately equal to V_g. $v_{sg}(t)$ can also have a dc component, not predicted by the circuit model.**

Secondary-side stray capacitances now lead to common-mode currents

Example: diode case-to-heatsink capacitance





$$V_{pp} = \frac{n-1}{2}\left(\frac{V_g}{n} + V\right)$$

These currents usually corrupt the ground reference voltage

Discussion

- Transformers can successfully provide dc and low-frequency ac isolation
- Transformer interwinding capacitances couple the primary and secondary voltages, greatly reducing the high-frequency ac isolation and leading to common-mode currents and conducted EMI

Some possible solutions:

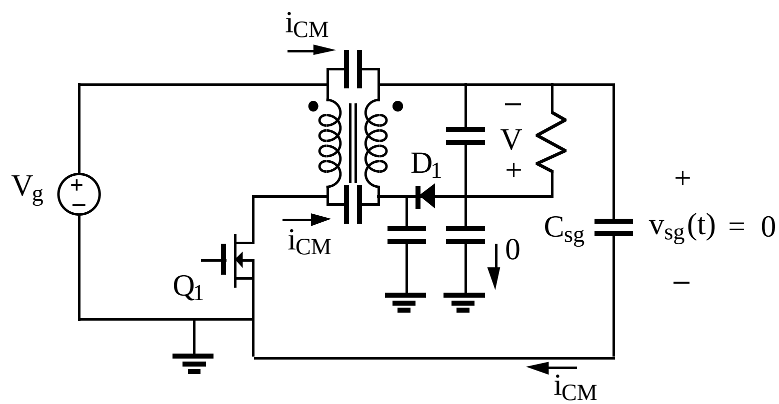
- Redesign the transformer to reduce the interwinding capacitance. This usually leads to increased leakage inductance
- Add common-mode filters:

  Capacitors which connect the primary- and secondary-side grounds

  Common-mode filter inductors

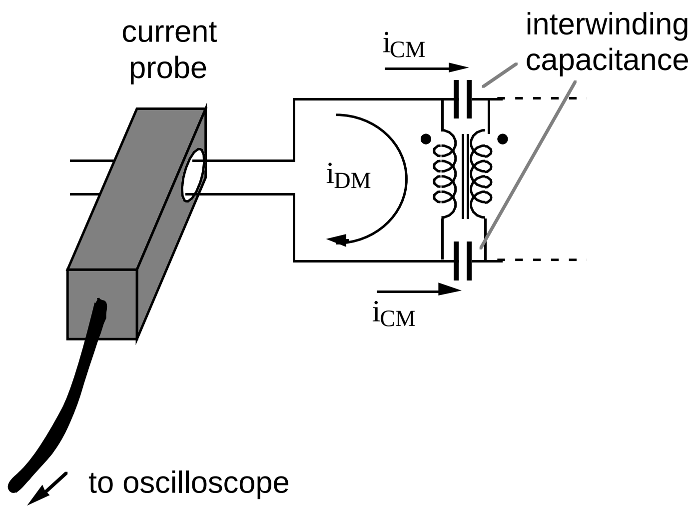
  This greatly reduces conducted EMI, and can also reduce radiated EMI. But the capacitors do not allow the secondary ground potential to switch at high frequency.

Addition of capacitance between primary and secondary grounds



Capacitor C_{sg} is much larger than the stray capacitances, and so nearly all of the common-mode current flows through C_{sg}. If C_{sg} is sufficiently large, then it will have negligible voltage ripple, and $v_{sg}(t)$ will no longer contain a high-frequency component.

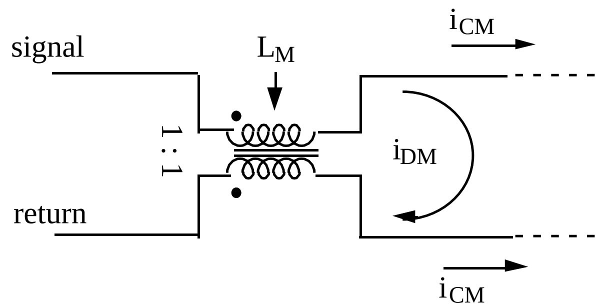
Measurement of common mode current



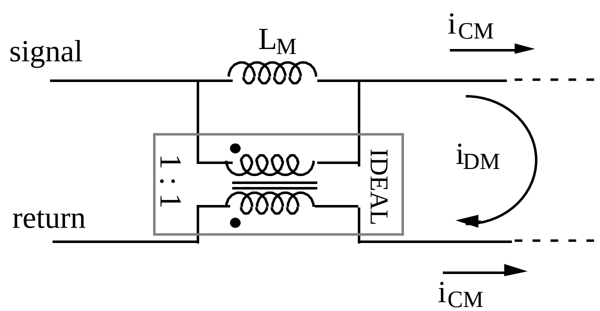
The common mode current due to transformer interwinding capacitance can be easily measured using a current probe

The differential-mode current $i_{DM}(t)$ cancels out, and the oscilloscope will display $2i_{CM}(t)$.

A Common-Mode Choke

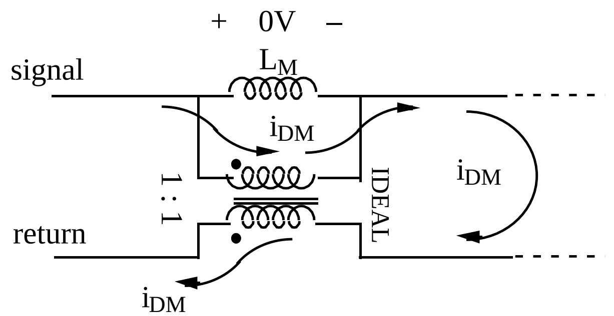


Equivalent circuit, including magnetizing inductance:



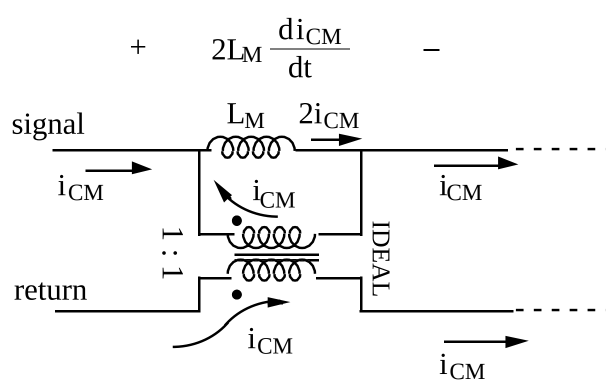
Operation of Common-Mode Choke

Differential mode



i_{DM} cancels out in windings, with no net magnetization of core. To the extent that the leakage inductance can be neglected, the common-mode choke has no effect on the differential-mode currents.

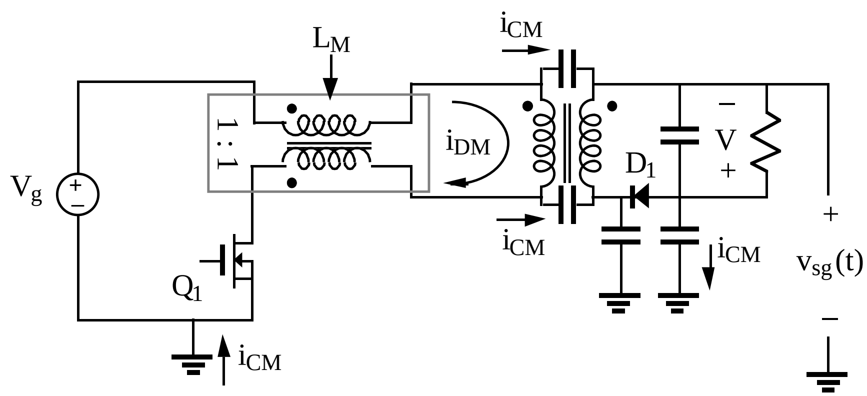
Common mode



The common-mode currents effectively add, magnetizing the core. The common-mode choke presents inductance L_M to filter these currents.

Use of a common-mode choke

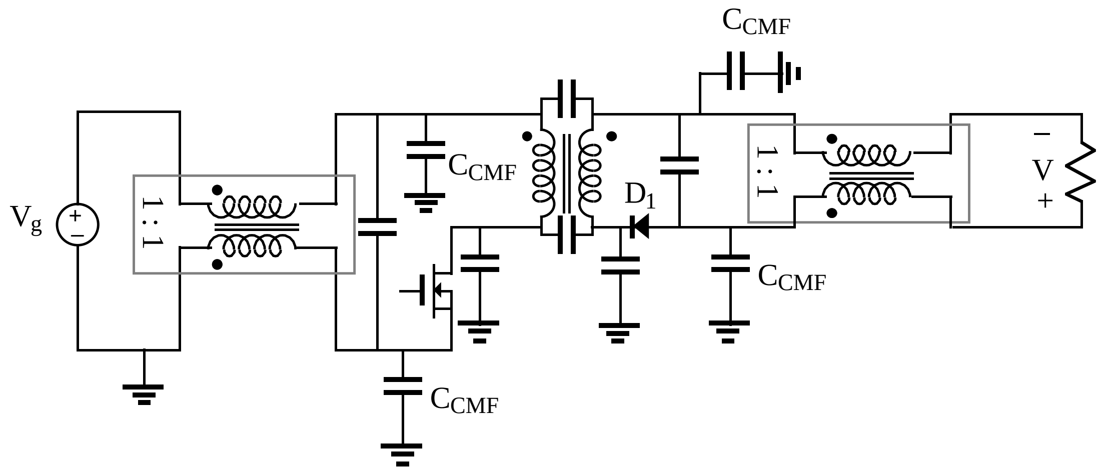
to reduce the magnitude of currents in transformer interwinding capacitances



Common-mode choke inserts inductance L_M to oppose flow of high-frequency common-mode currents

Use of common-mode chokes

to filter the power supply input and output



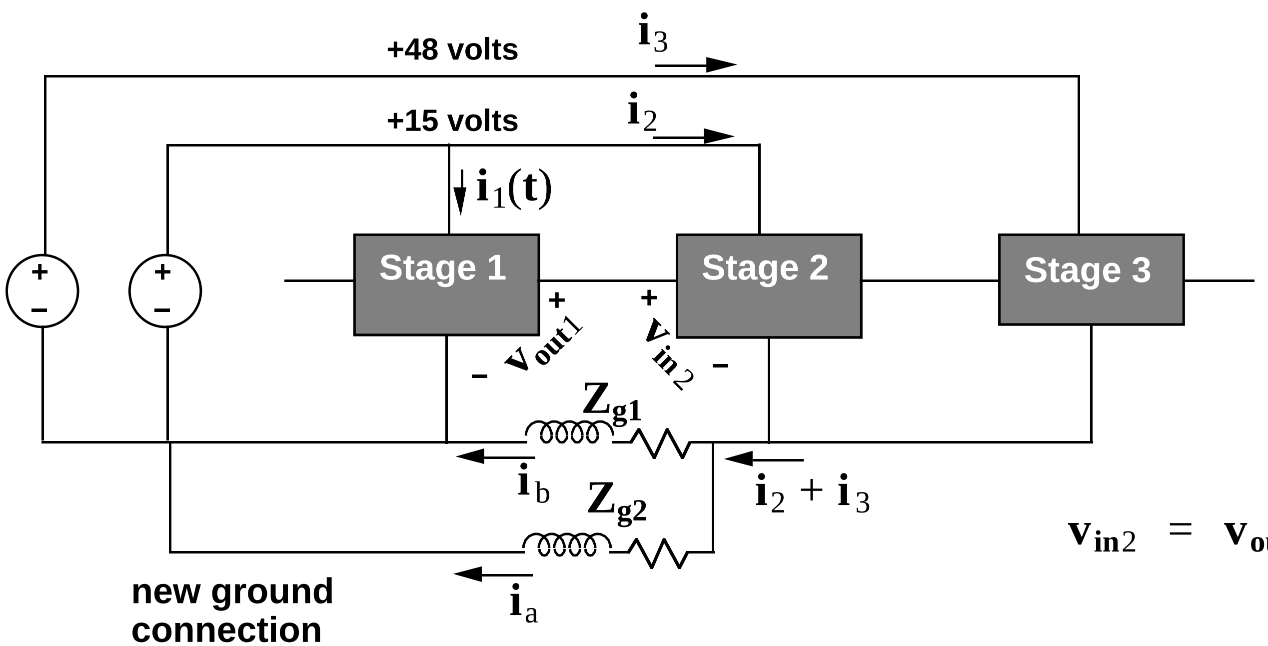
The common-mode chokes, along with the capacitors C_{CMF}, form two-pole low pass filters which oppose the flow of high-frequency common-mode currents

Use of a common-mode choke

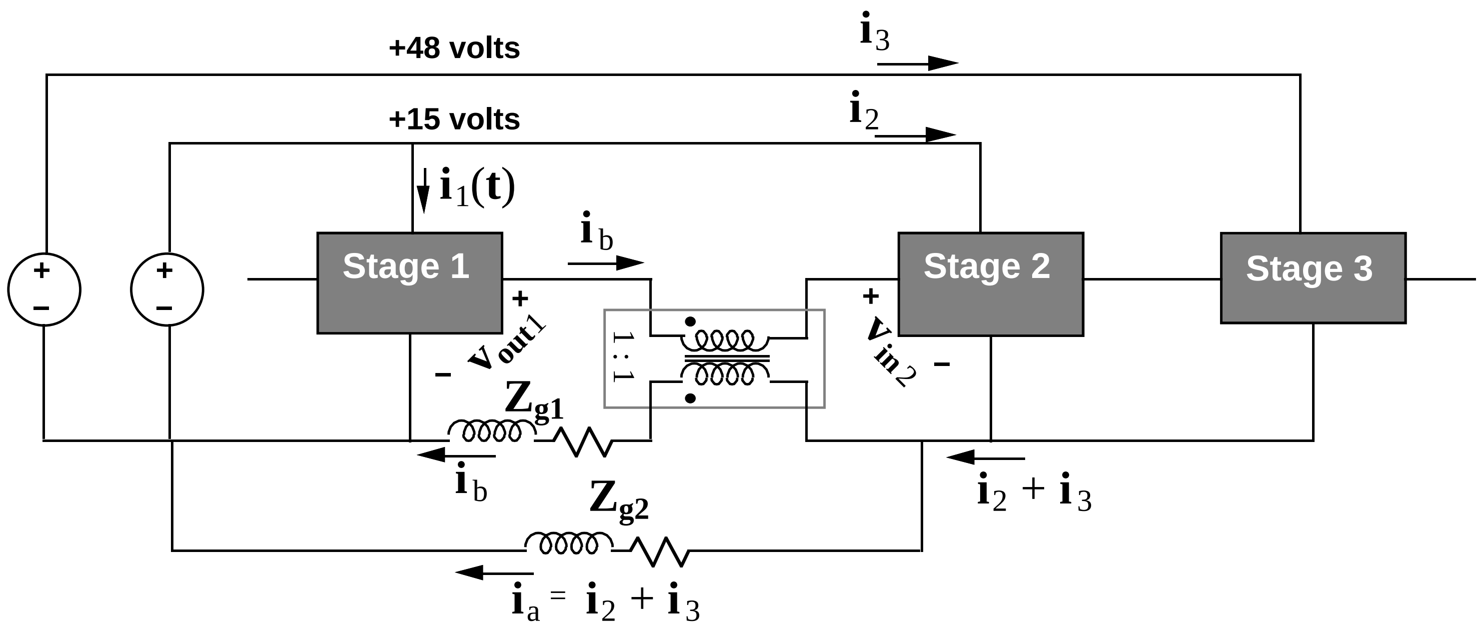
to prevent corruption of ground reference voltage

Back to example of slide #14:

Attempt to prevent coupling of signal ($i_2 + i_3$) into input signal v_{in2} by adding another ground connection, for conduction of return current ($i_2 + i_3$). This requires that $i_a = (i_2 + i_3)$.



$$v_{in2} = v_{out1} - Z_{g1}\, i_b$$



The common-mode choke forces the high frequency return current ($i_2 + i_3$) to flow through the alternate ground path: $i_a = (i_2 + i_3)$. The return current i_b is equal to the signal current flowing between stages 1 and 2.

Summary

EMI ("Noise") is caused by the violation of idealizing assumptions:
- **Imperfect conductors**
- **Corruption of zero-potential ground reference**
- **Stray capacitances**

Inductance of wires
- **Keep areas of high frequency loops as small as possible**

Coupling of signals via impedance of ground connections
- **Steer ground currents away from sensitive circuits**
- **Examples: power return, gate drive return, coupling of signals from one stage to the next**
- **Use ground planes in sensitive analog portions of system**

Coupling of signals via magnetic fields
- **Ground loops and circulating ground currents**
- **Example: audiosusceptibility measurement**

Coupling of signals via electric fields

- **Stray capacitances**
- **Example: drain-to-heatsink capacitance**
- **Example: transformer interwinding capacitances**

Common mode noise

- **Usually caused by stray capacitances**
- **Can be filtered using common-mode chokes and common-mode filter capacitors**

It is possible to figure out where the EMI is being generated, and to engineer the circuit to mitigate its effects