# Course Info

- Course focuses on design an modeling of “high frequency” power electronics
  - Course website: http://web.eecs.utk.edu/~dcostine/ECE581
  - Goal of course is understanding of motivations and issues with high frequency power electronics; analysis and design techniques; applications
- Prerequisites: undergraduate Circuits sequence, Microelectronics, ECE 481 – Power Electronics, or equivalent



# Contact Info

**Instructor:** Daniel Costinett

- Office:  MK504
- OH: T: 11-12, W:9-10, By appointment
- E-mail: Daniel.Costinett@utk.edu
- Email questions will be answered within 24 hours (excluding weekends)
- Please use **[ECE 581]** in the subject line

# Course Structure

- Course meets MWF 10:10-11:-0 am
- Plan to spend ~9 hours per week on course outside of lectures
- Grading:
  - Homework/Lab: 40%
    - One homework per week
    - Assignments due on Fridays unless otherwise noted on course website
    - One design competition outside of class time
  - Midterm: 25%
    - Tentatively scheduled for October 29th
  - Final: 35%



# Assignments

- Assignments due *at the start of lecture* on the day indicated on the course schedule
- No late work will be accepted except in cases of documented medical emergences
- Collaboration is encouraged on all assignments except quizzes and exams; Turn in your own work
- All work to be turned in through canvas

# Textbook and Materials

- The textbook

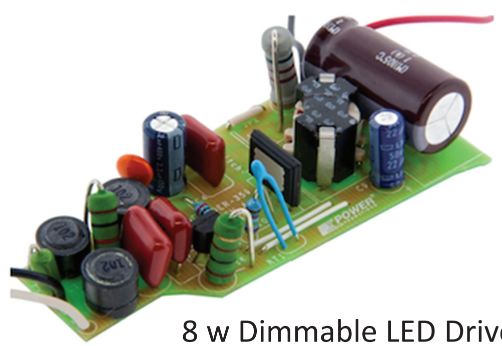
  R.Erickson, D.Maksimovic, *Fundamentals of Power Electronics*, Springer 2001

  will reference chapters 19-20 and reference materials from prior chapters. The textbook is available on-line from campus network. Purchase is not required for this course.
- MATLAB/Simulink, LTSpice will be used; All installed in the Tesla Lab
- Lecture slides and notes, additional course materials, homework, due dates , etc. posted on the course website
- Additional information on course website



# Introduction

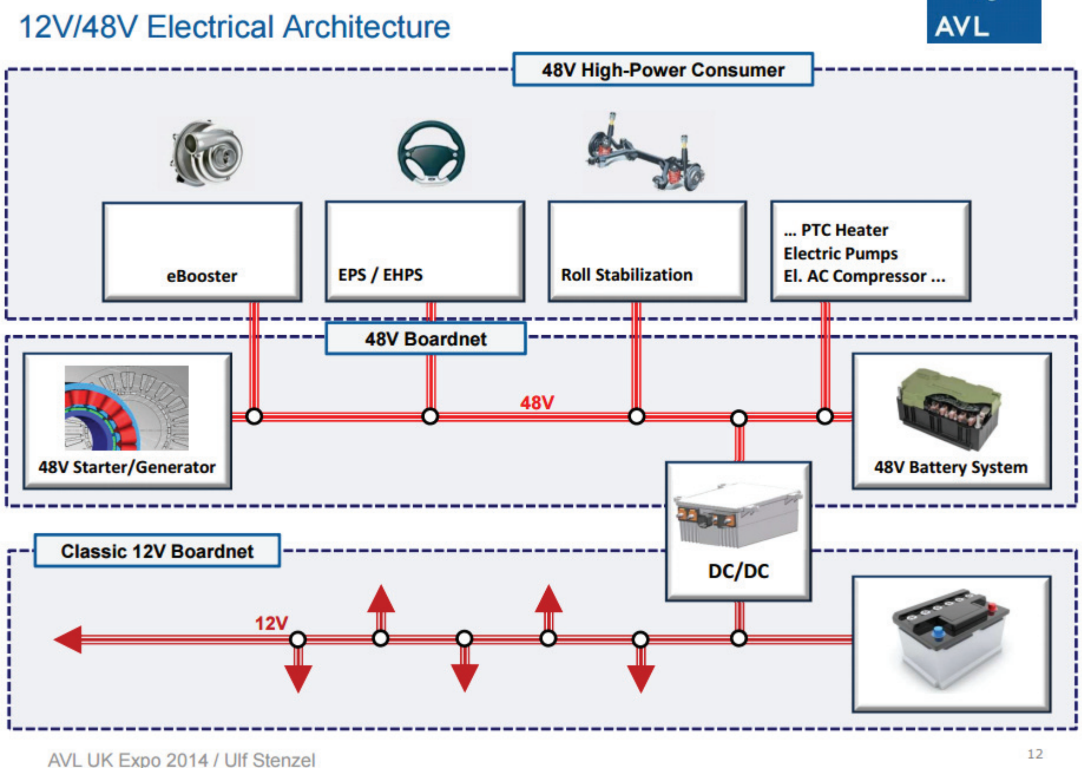
- Why high frequency?
  - Power Density
  - Control Bandwidth
- Techniques
  - Devices
  - Control
  - Topologies
  - Passives



8 w Dimmable LED Driver

Voltage Regulation Module

# Motivating Example

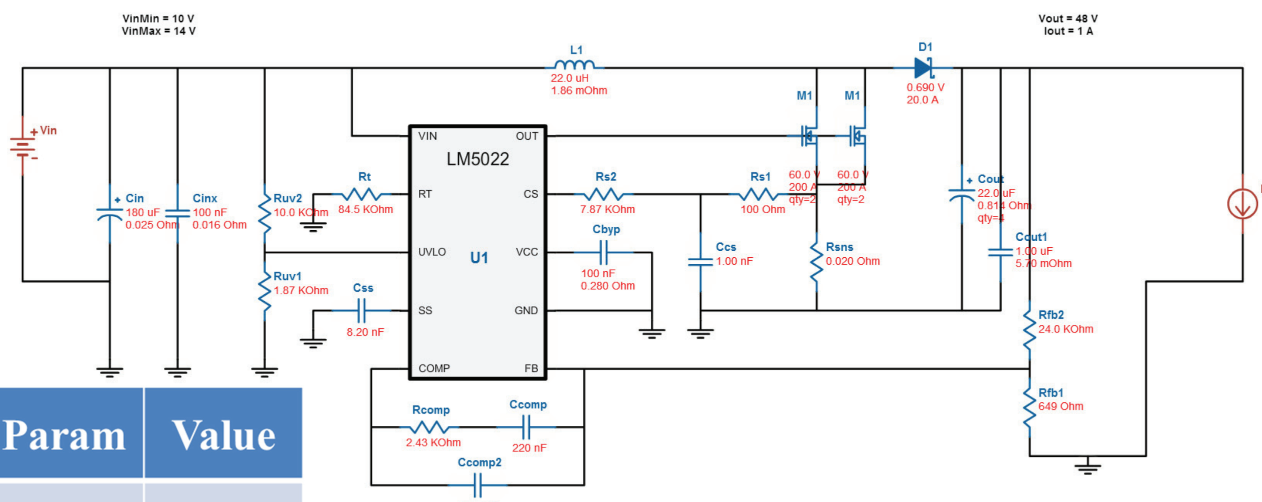



NXP Semi, "Semiconductors – enablers of future mobility concepts", 2011
Audi, "Electric biturbo and hybridization", 2014
AVL, "48V Mild Hybrid Systems"



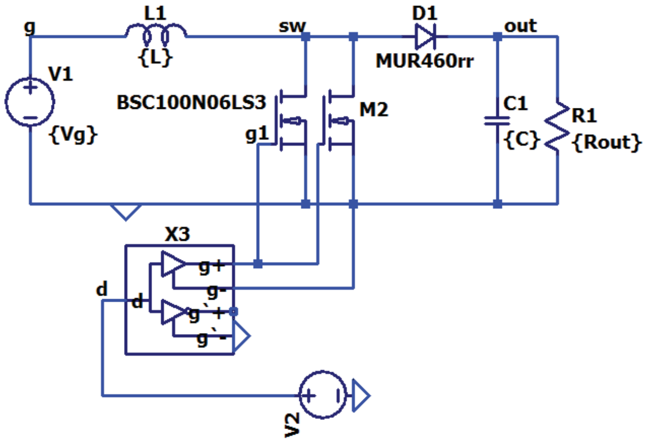
# Baseline Design

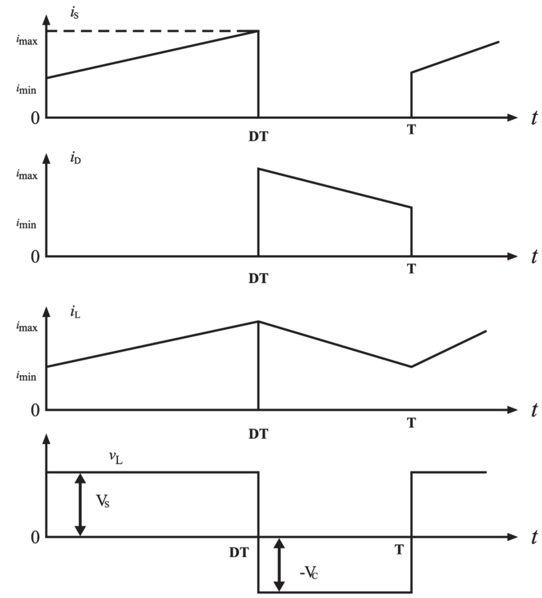
- Use TI WebBench (webench.ti.com) to get a baseline design




| Param | Value |
|---|---|
| $V_g$ | 12 V |
| $V_{out}$ | 48 V |
| $R_{out}$ | 48 Ω |
| $\Delta V_{out}$ | 0.1 V |

# LTSpice Simulation

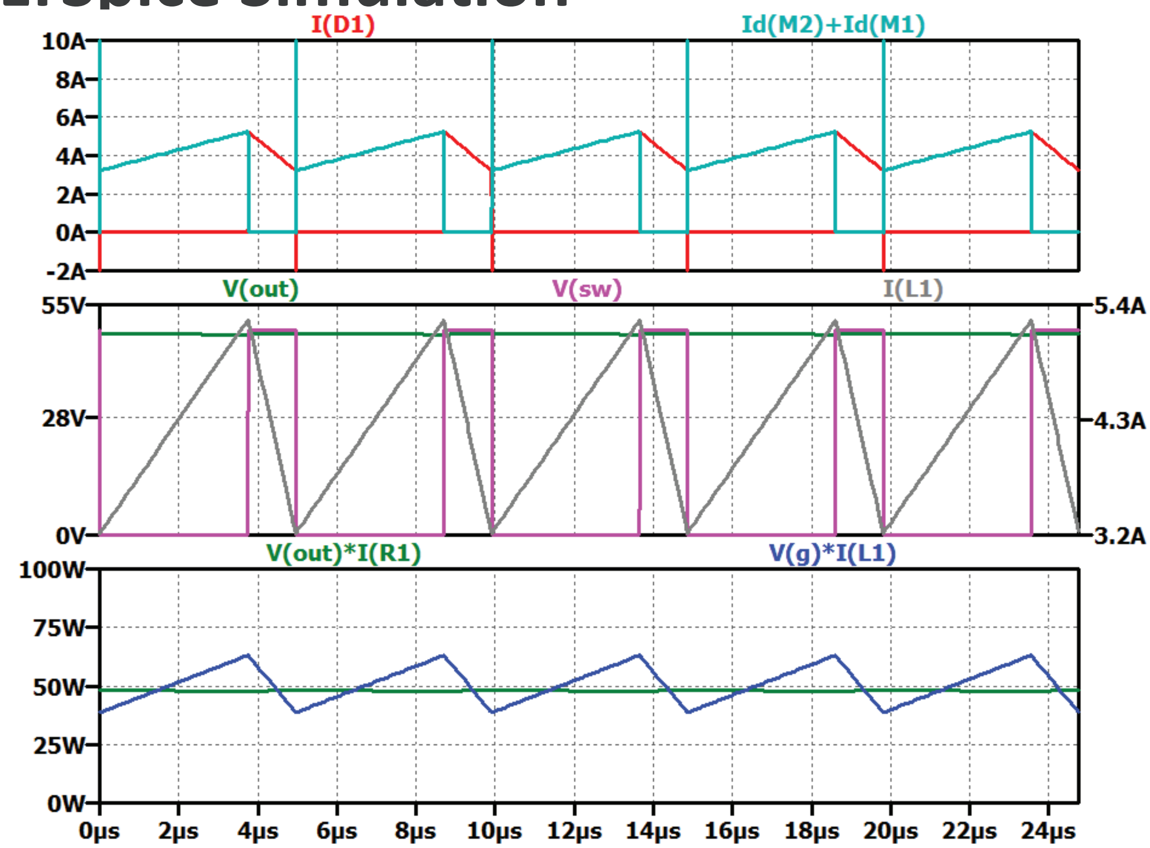


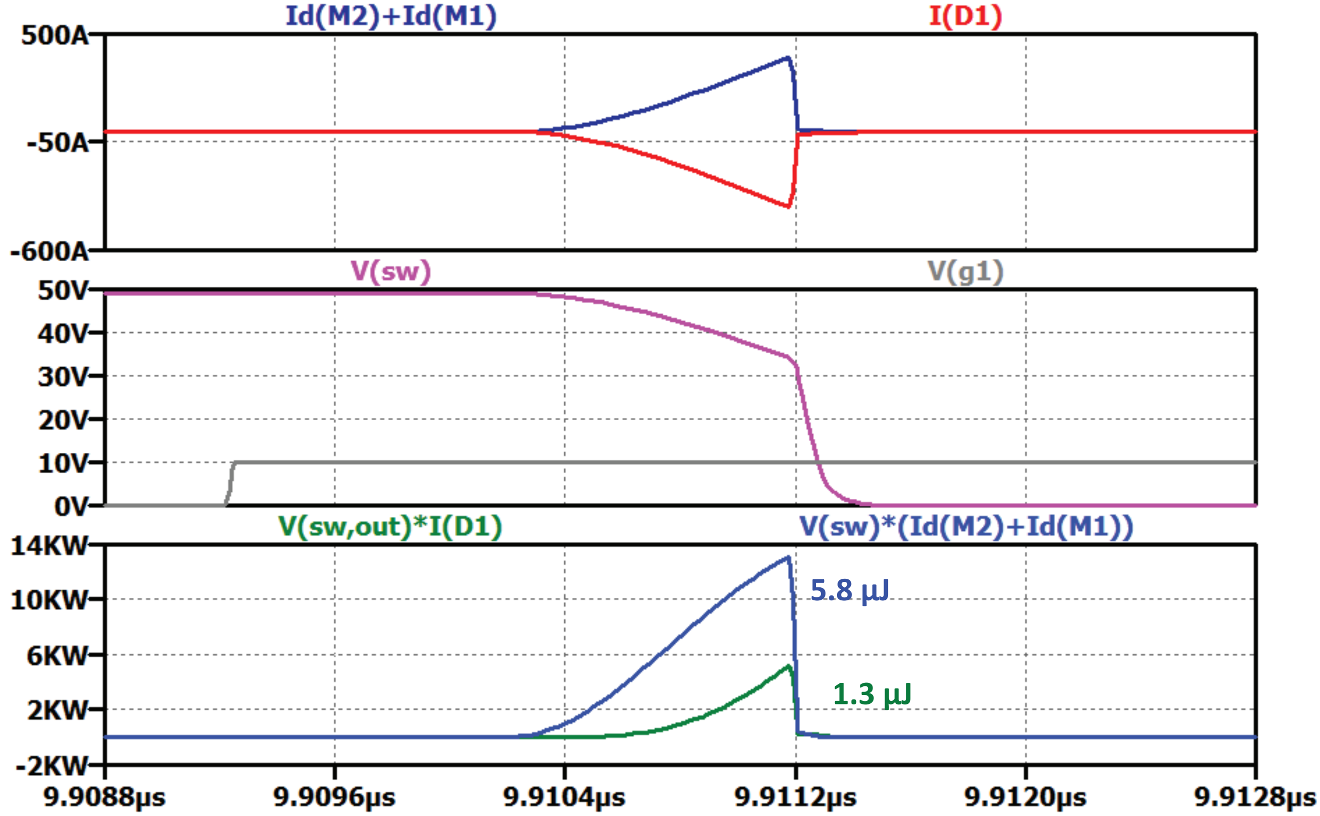

| $L$ | $C_{out}$ | $f_s$ | Diode | $\eta$ (Sim) |
|---|---|---|---|---|
| 22uH | 22uF | 202k | Si (FR) | 93.9% |



# LTSpice Simulation

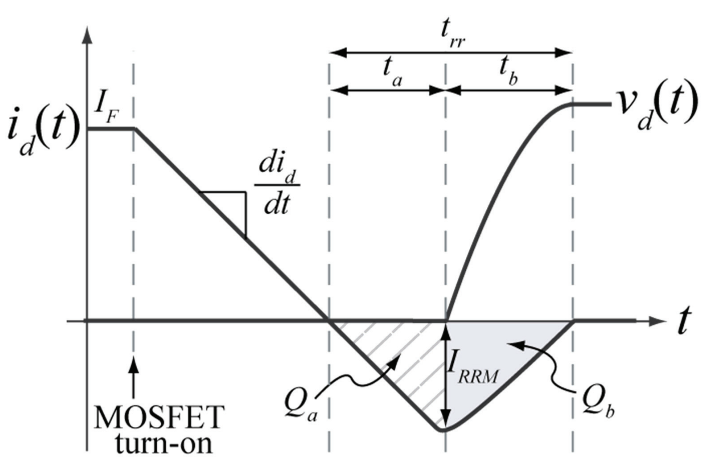


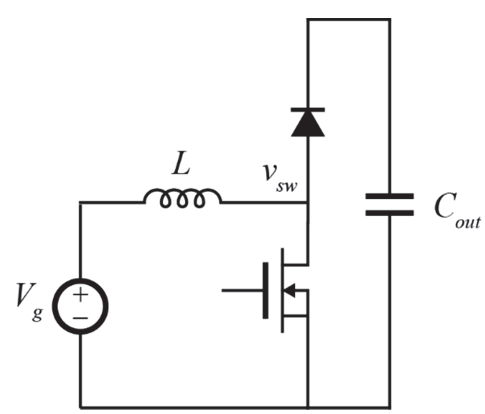
# Switching Transition






# Diode Reverse Recovery



# Datasheet RR Characteristics

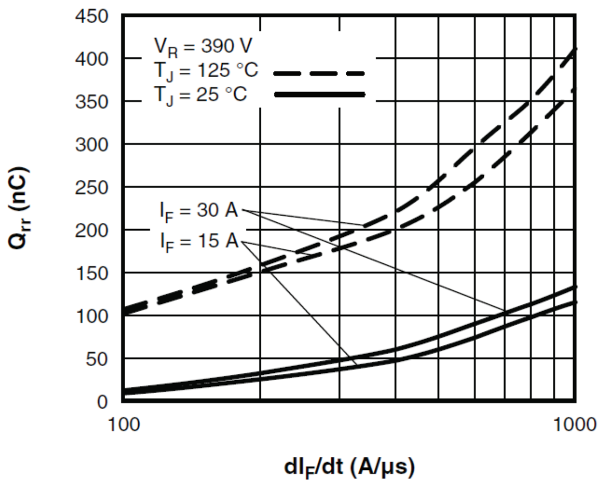



Fig. 10 - Typical Stored Charge vs. $dI_F/dt$

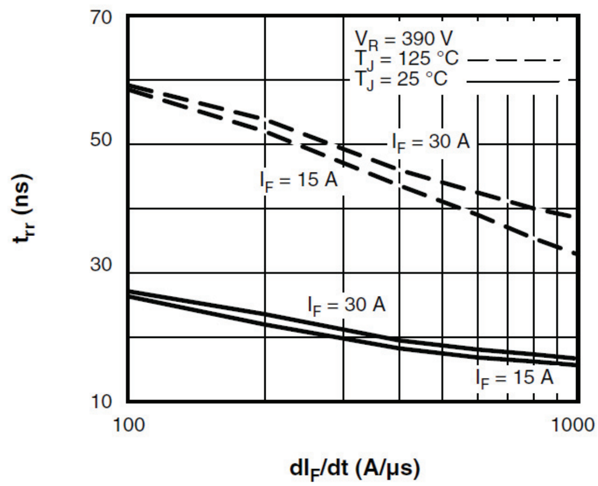
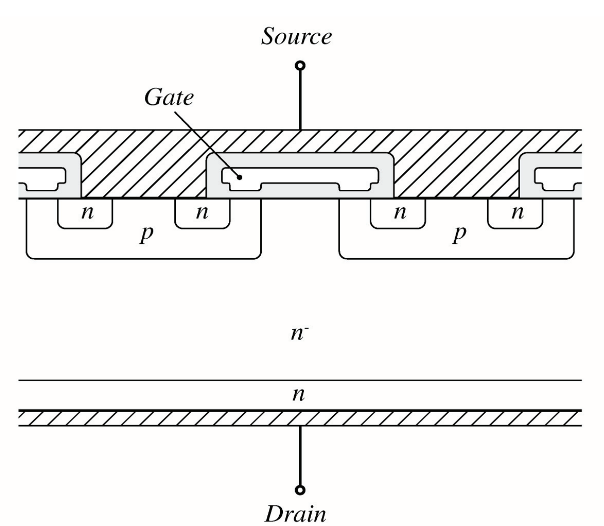
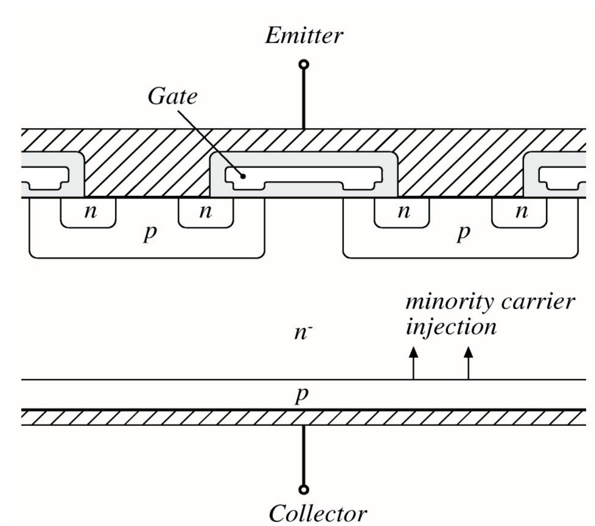



Fig. 9 - Typical Reverse Recovery Time vs. $dI_F/dt$

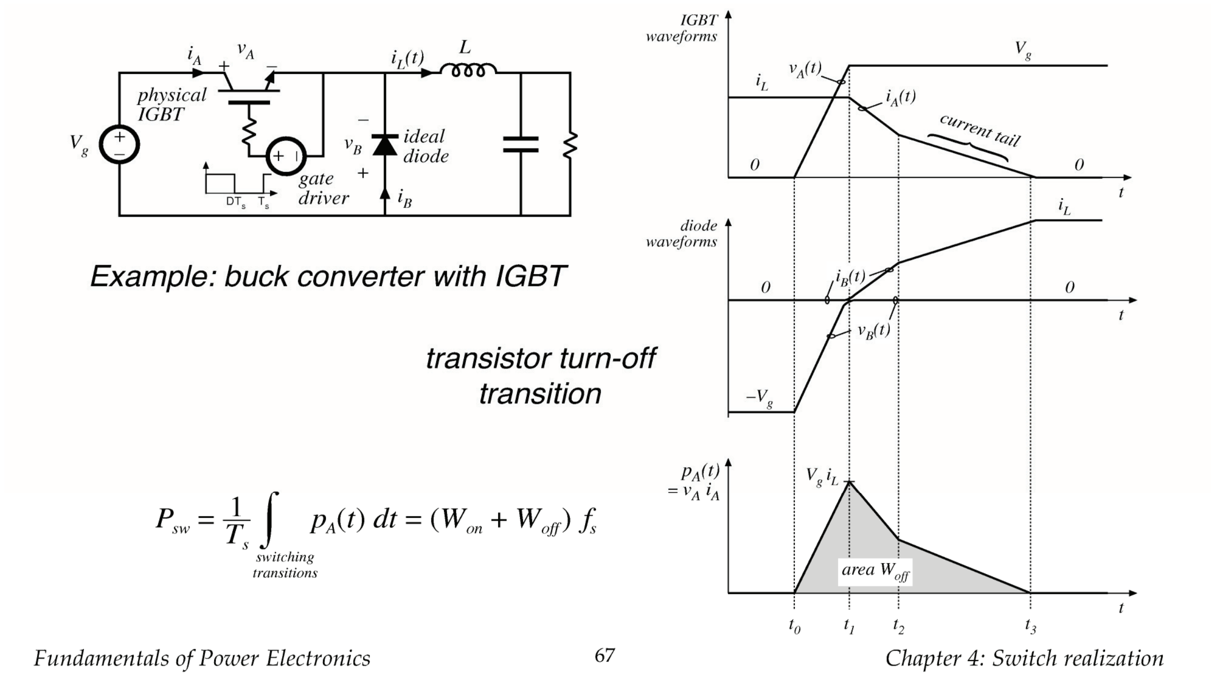


# Charge Storage



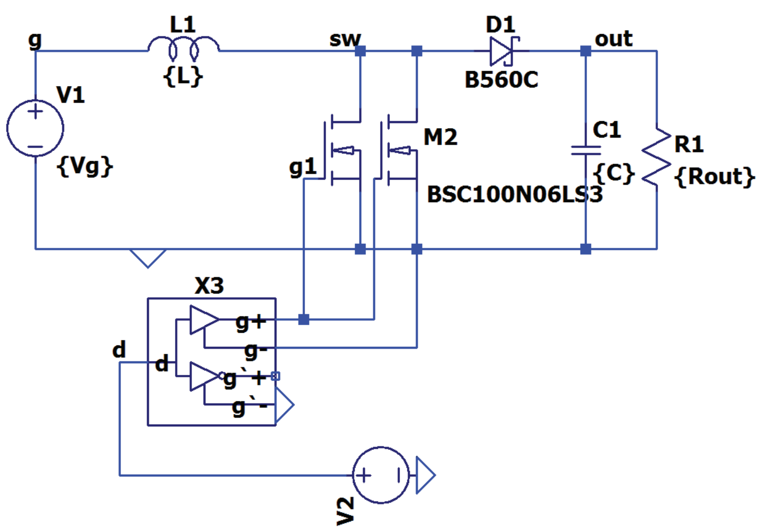



# IGBT Current Tailing



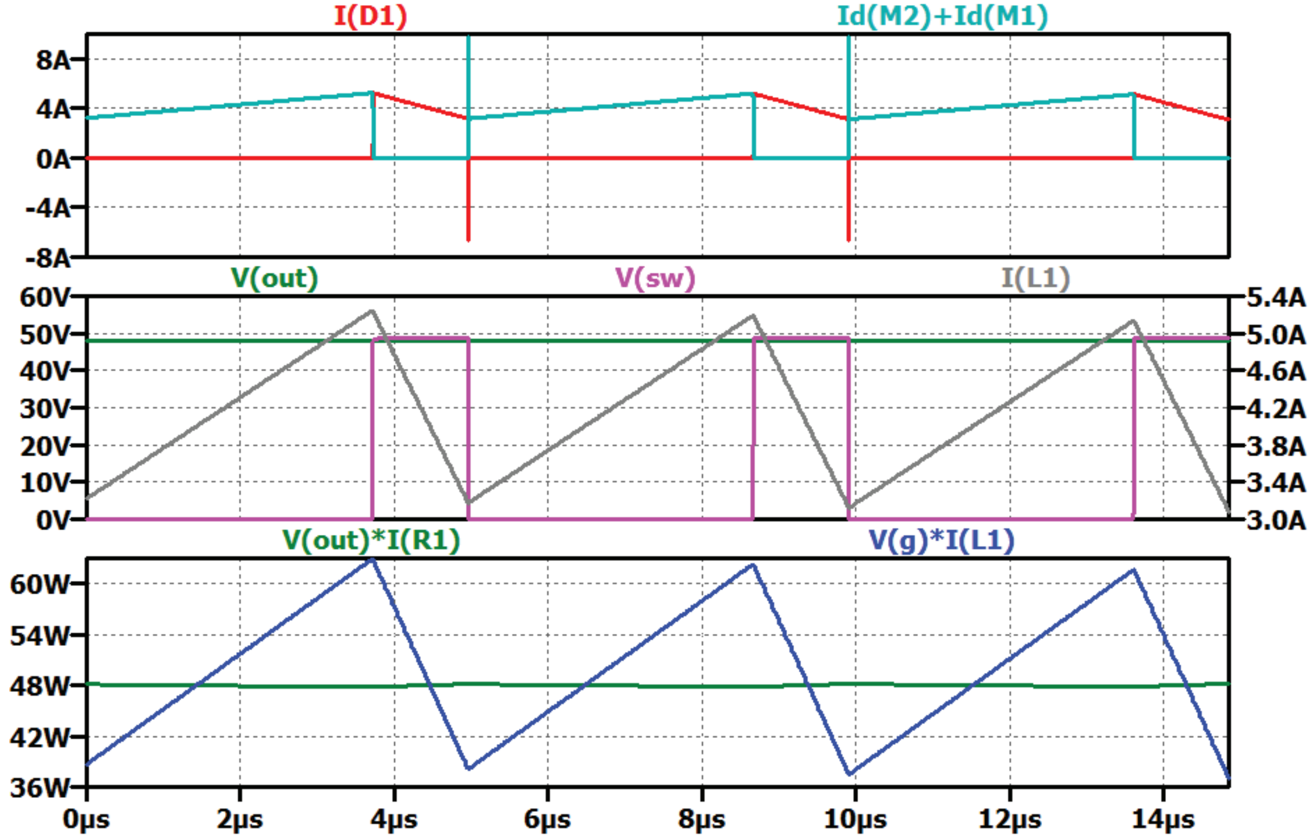



# Schottky Diode



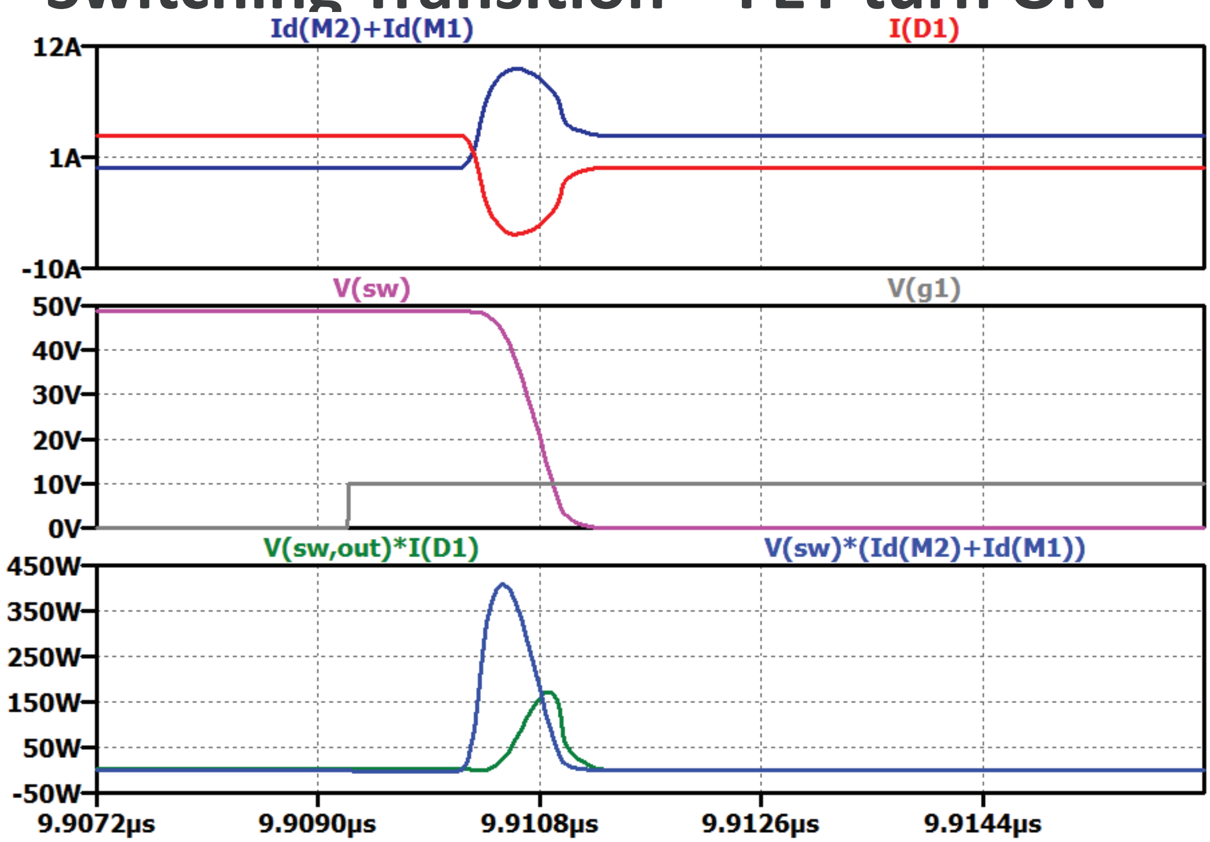

| $L$ | $C_{out}$ | $f_s$ | Diode | $\eta$ (Sim) |
|---|---|---|---|---|
| 22uH | 22uF | 202k | Si (FR) | 93.9% |
| 22uH | 22uF | 202k | Si Schottky | 95.8% |

# Simulation Waveforms

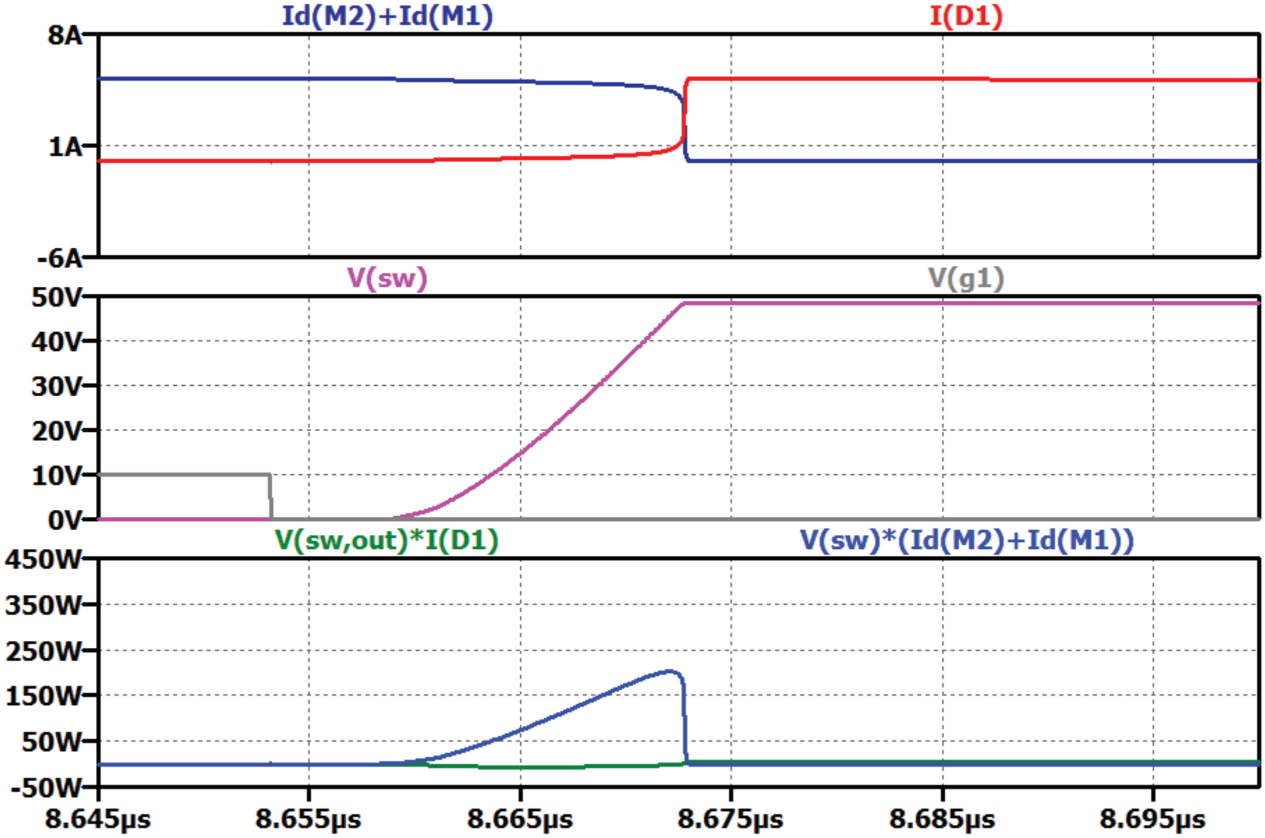





# Switching Transition – FET turn ON



# Switching Transition – FET turn OFF



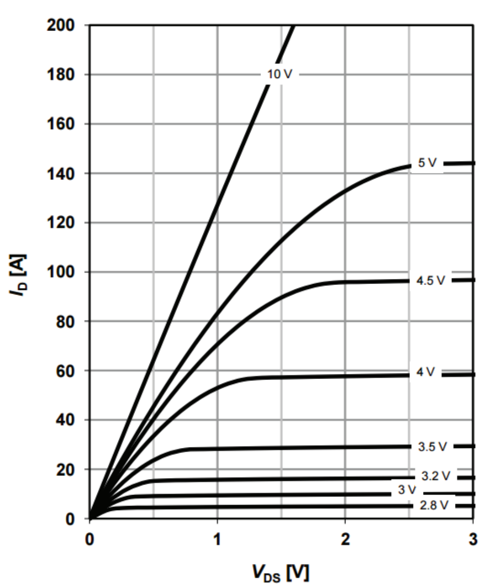



# MOSFET Switching Behaviors

**5 Typ. output characteristics**

$I_D$=f($V_{DS}$); $T_j$=25 °C

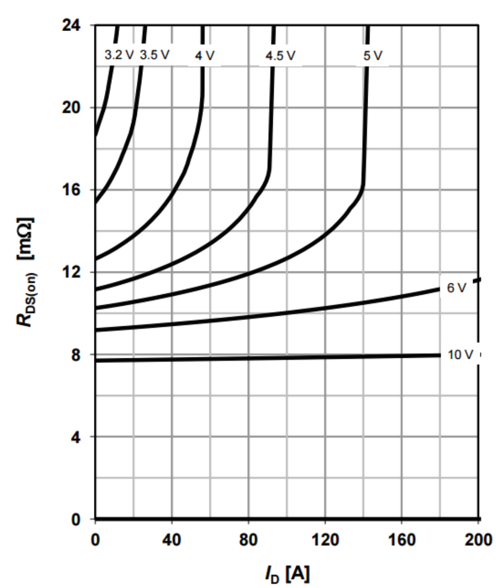
parameter: $V_{GS}$



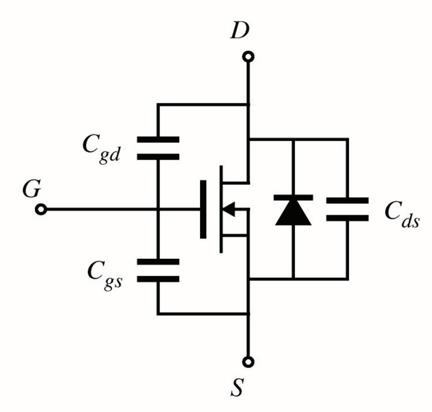

**6 Typ. drain-source on resistance**

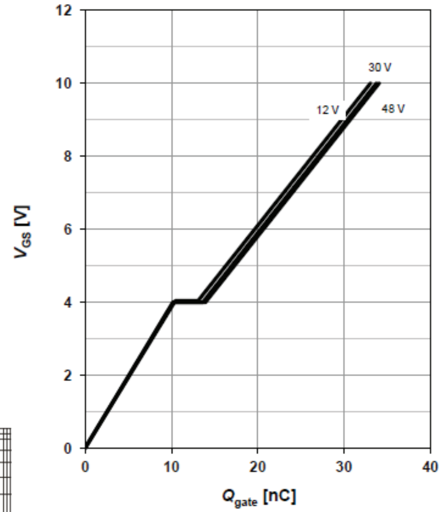
$R_{DS(on)}$=f($I_D$); $T_j$=25 °C

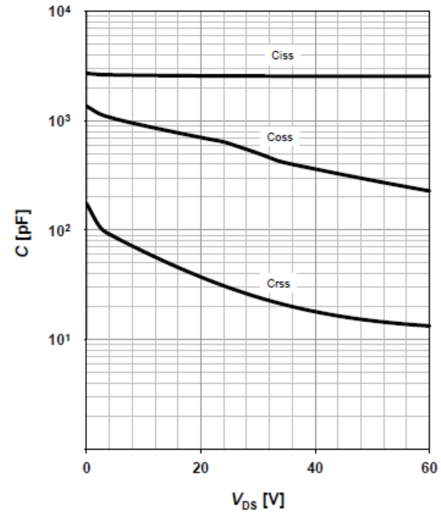
parameter: $V_{GS}$

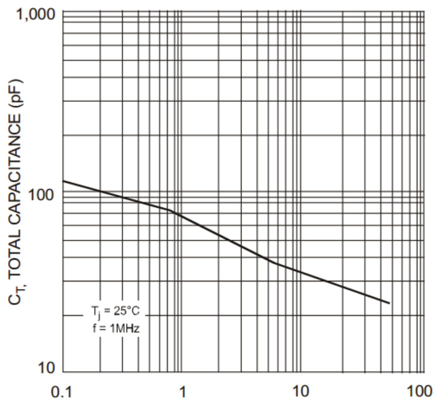


# MOSFET Stored Charge



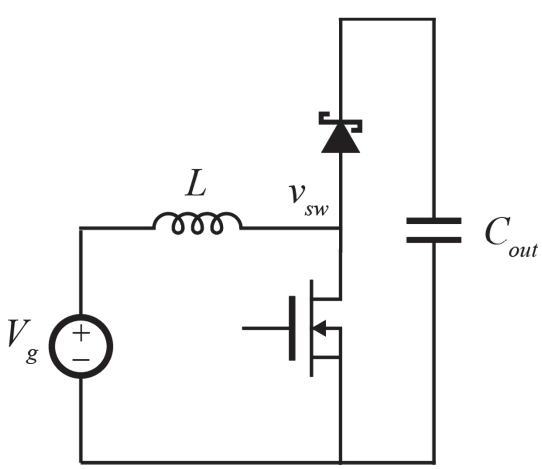



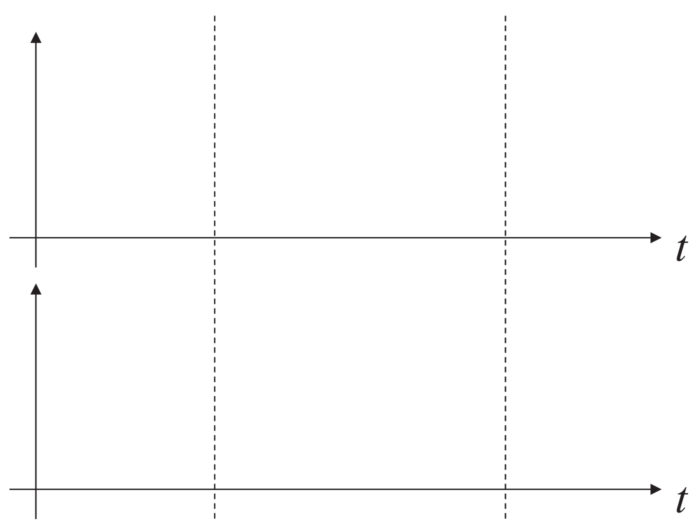



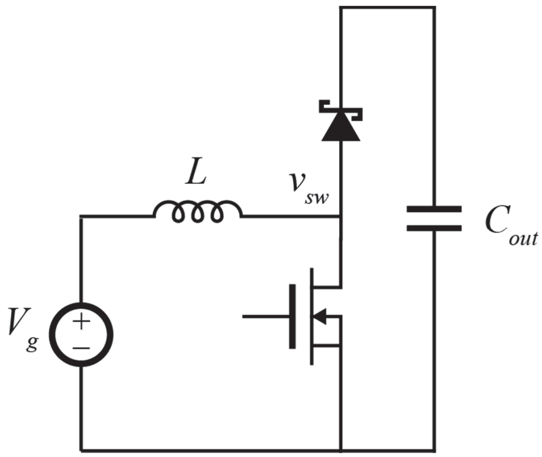


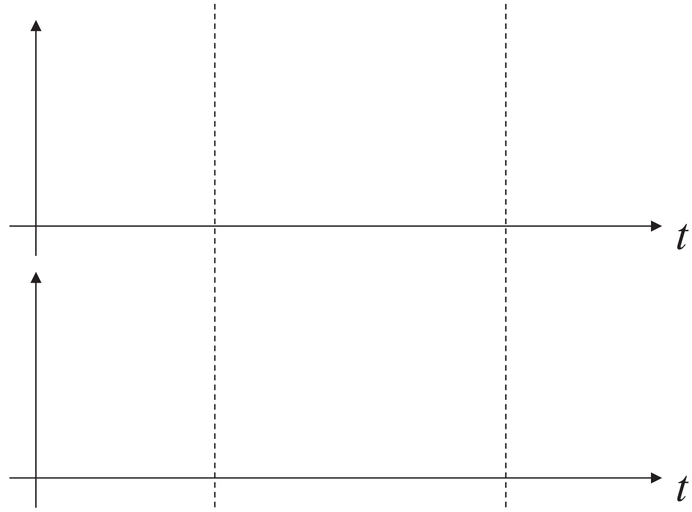

# Device Capacitances



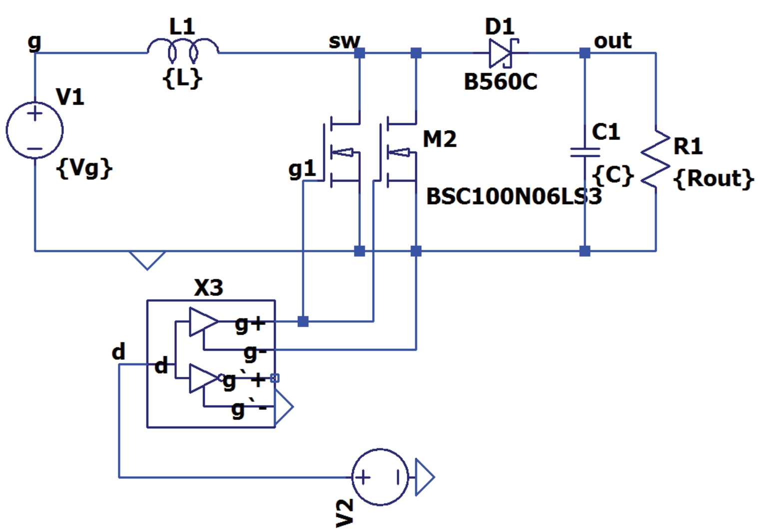
# Device Capacitances



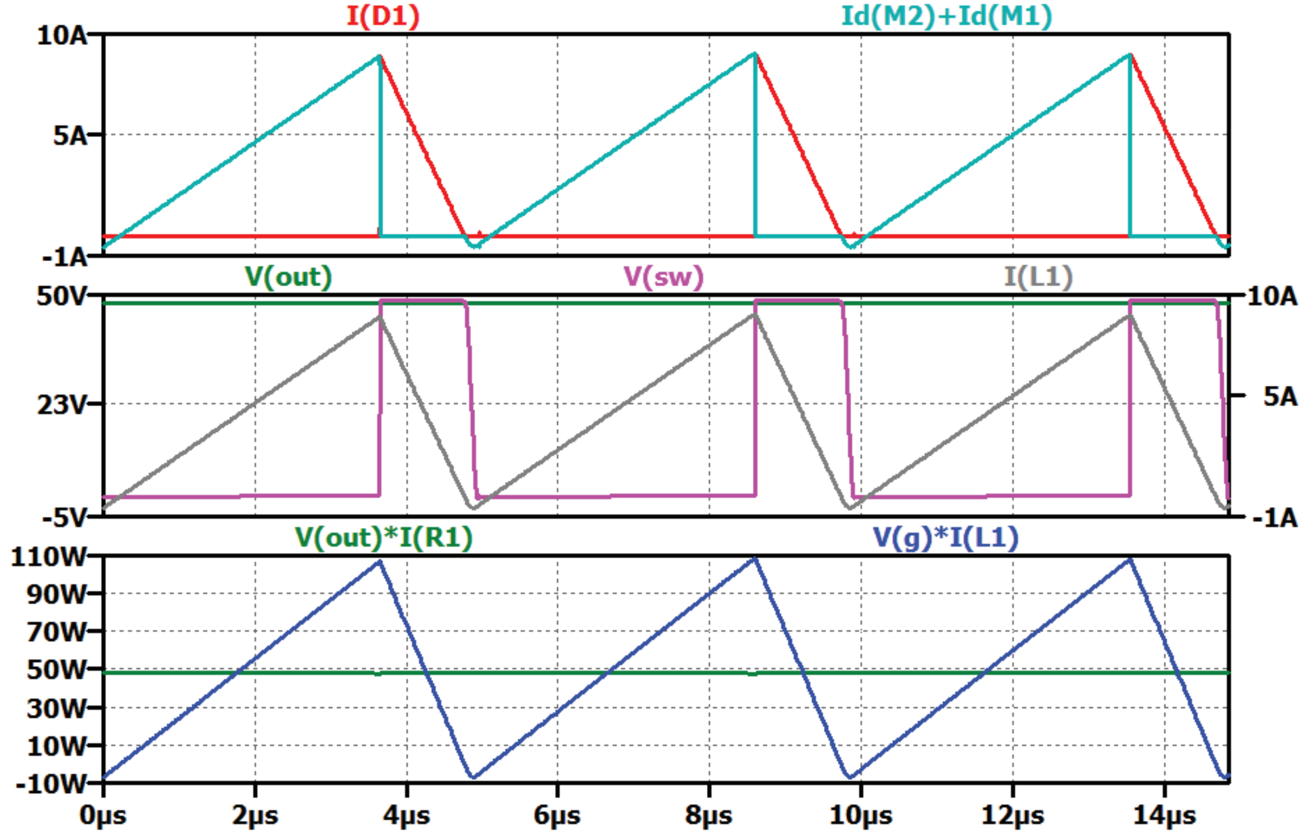



# DCM: Soft Switching



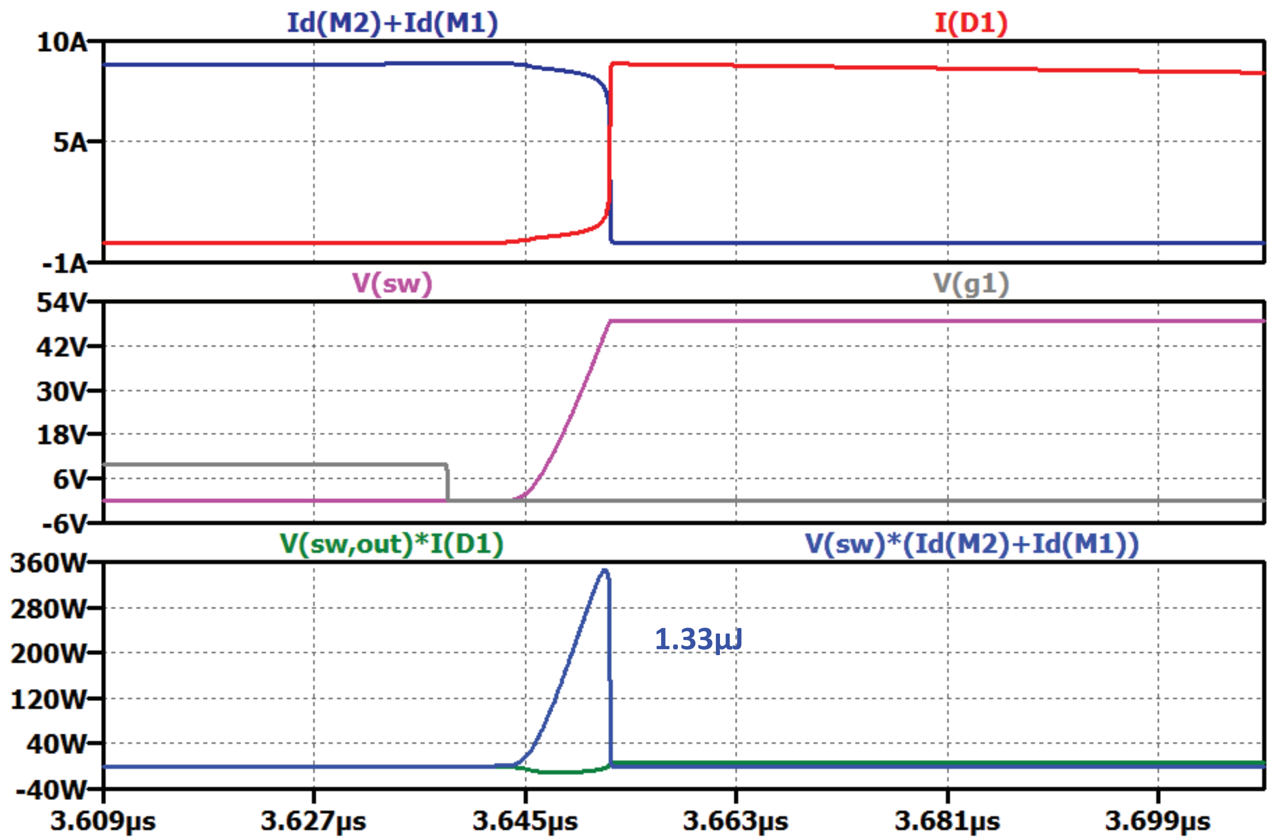

| $L$ | $C_{out}$ | $f_s$ | Diode | $\eta$ (Sim) |
|---|---|---|---|---|
| 22uH | 22uF | 202k | Si (FR) | 93.9% |
| 22uH | 22uF | 202k | Si Schottky | 95.8% |
| 4.6uH | 22uF | 202k | Si Schottky | 98.2% |

# DCM Simulation

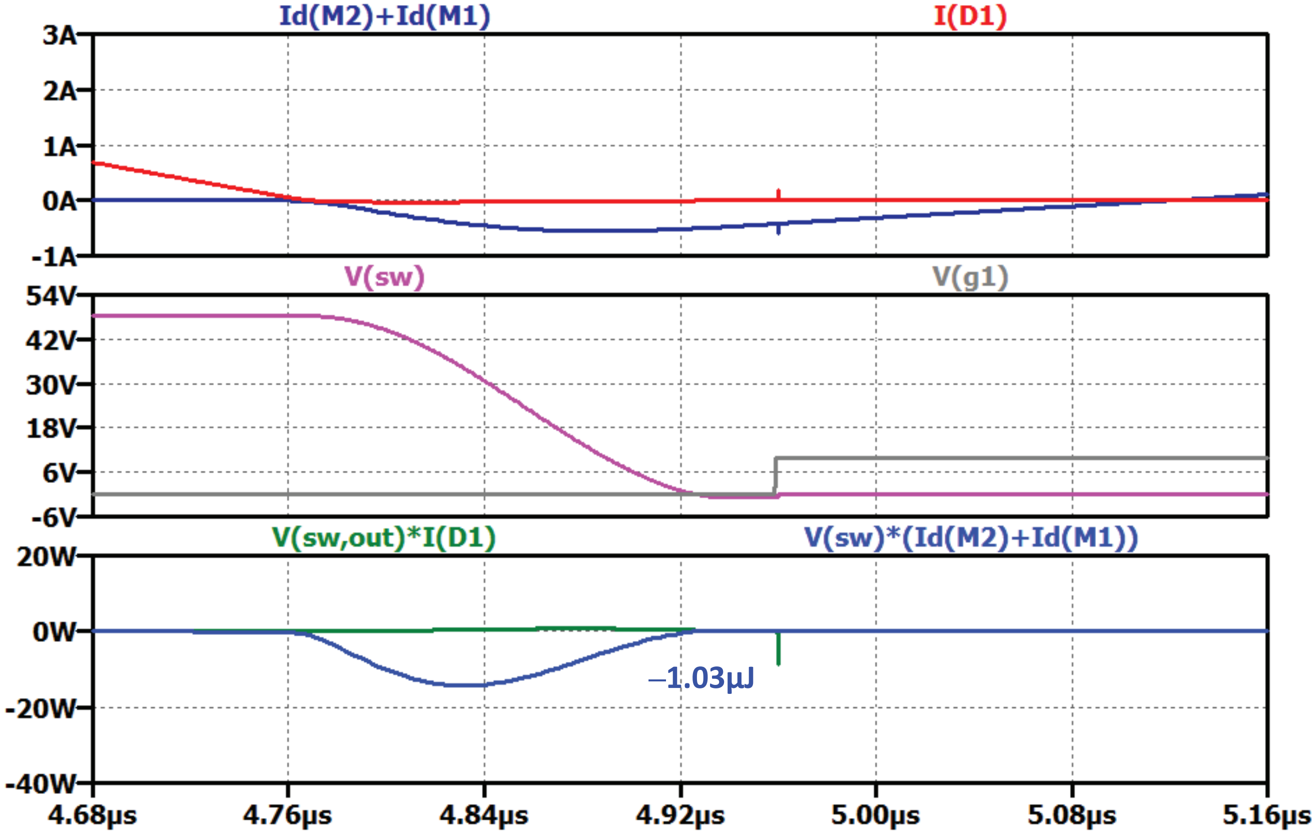





# MOSFET Turn-Off

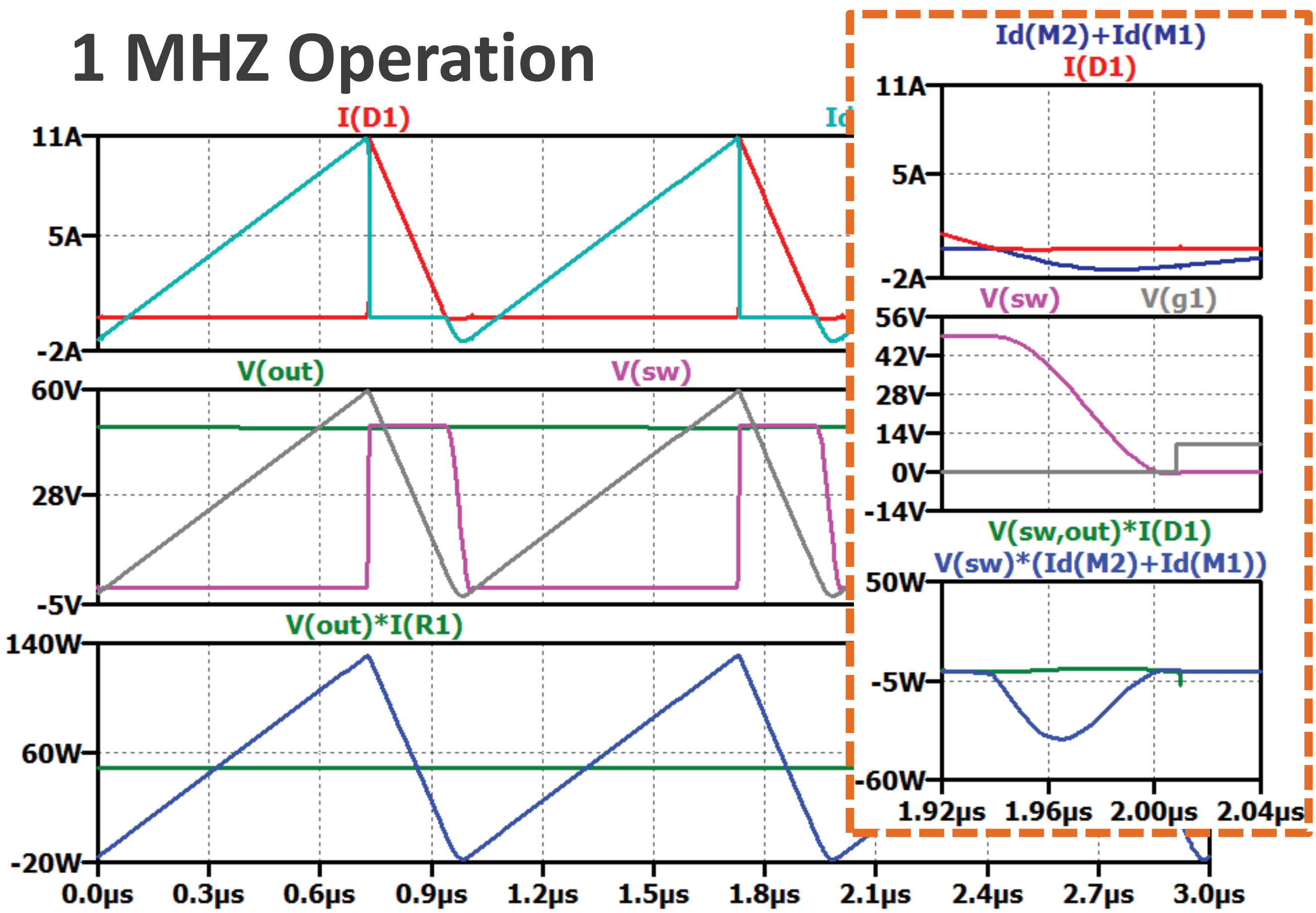


# MOSFET Turn-On

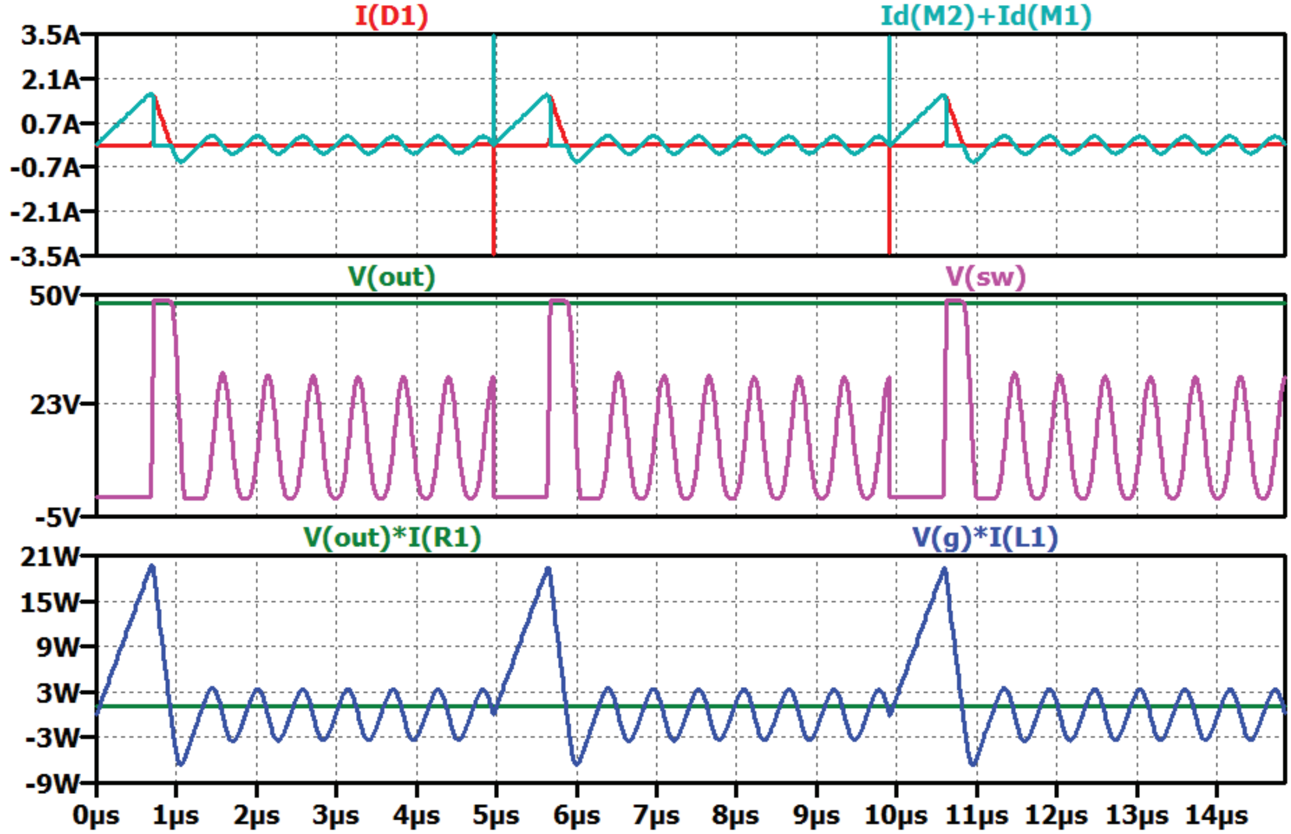





# 1 MHZ Operation

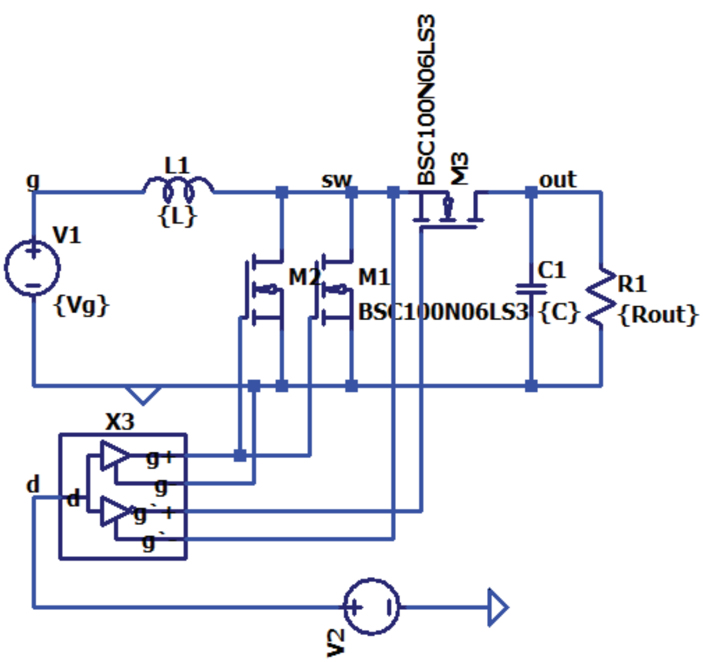


# Low Power Operation

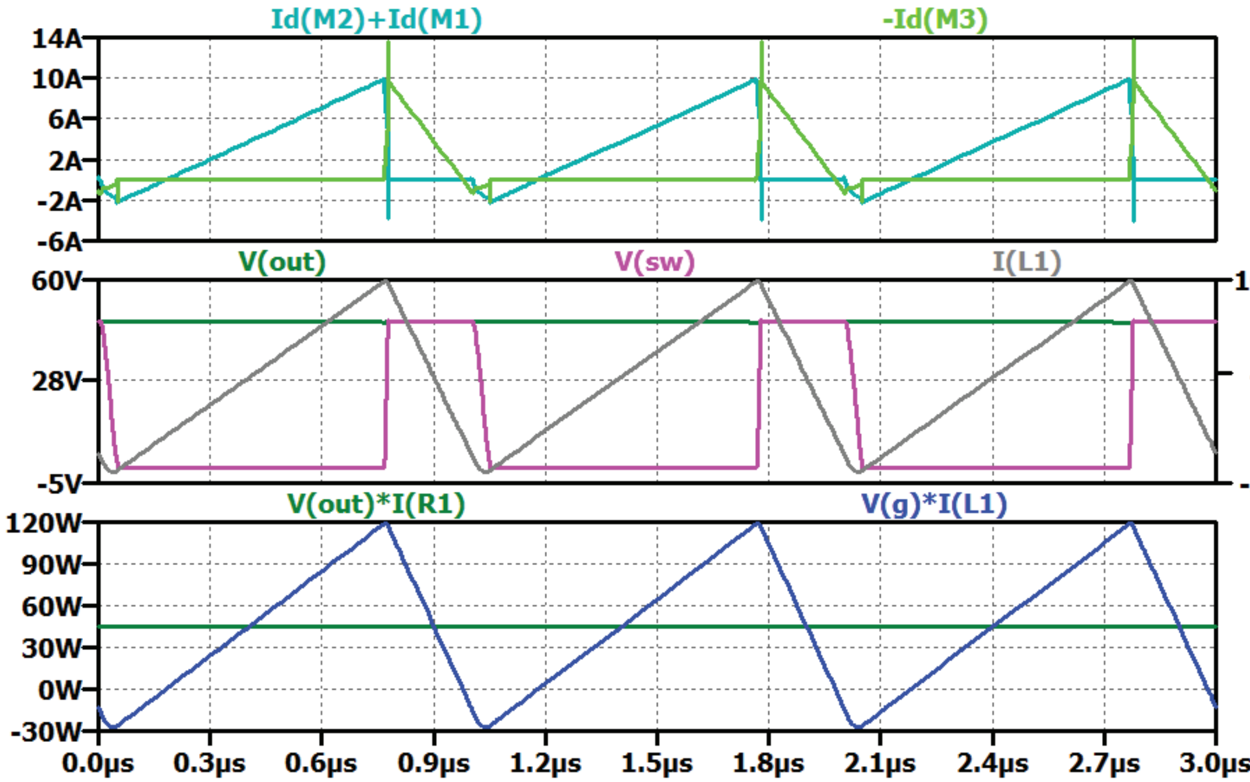





# Synchronous Operation

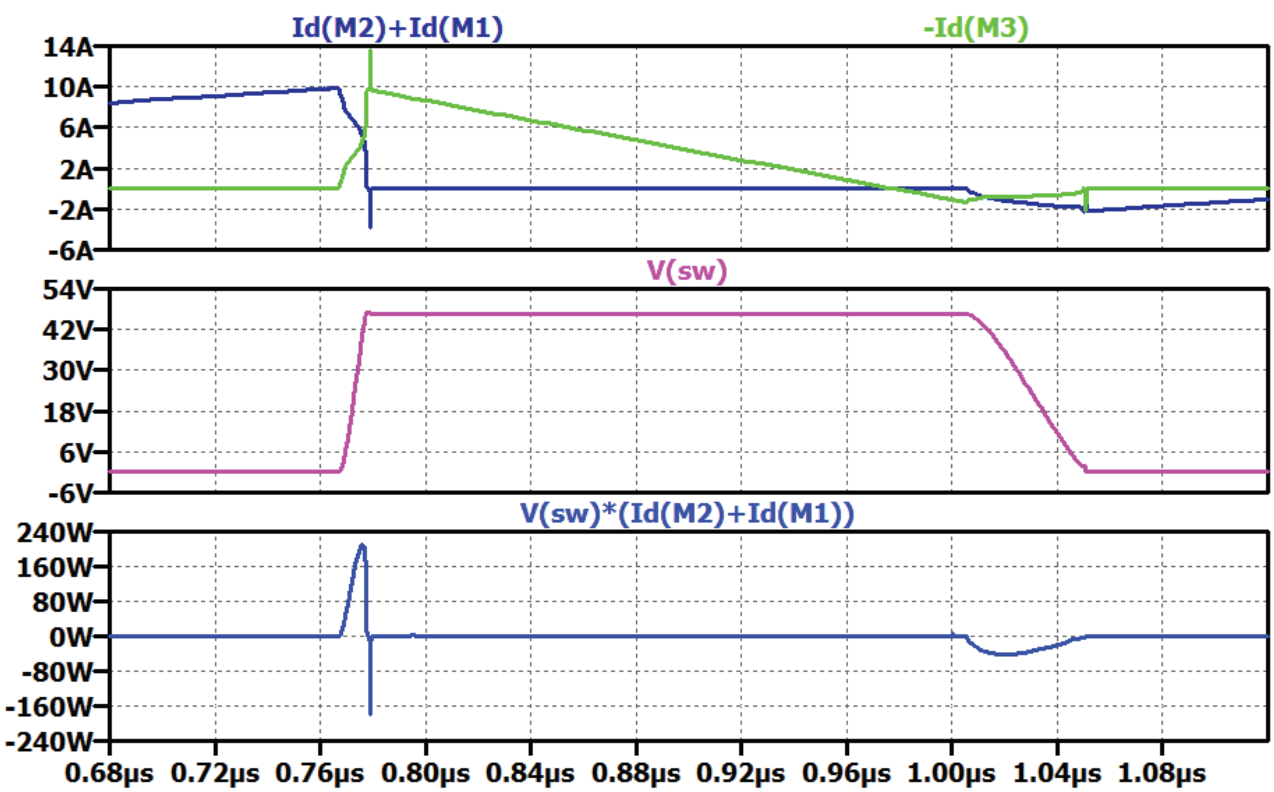


# Synchronous Simulation

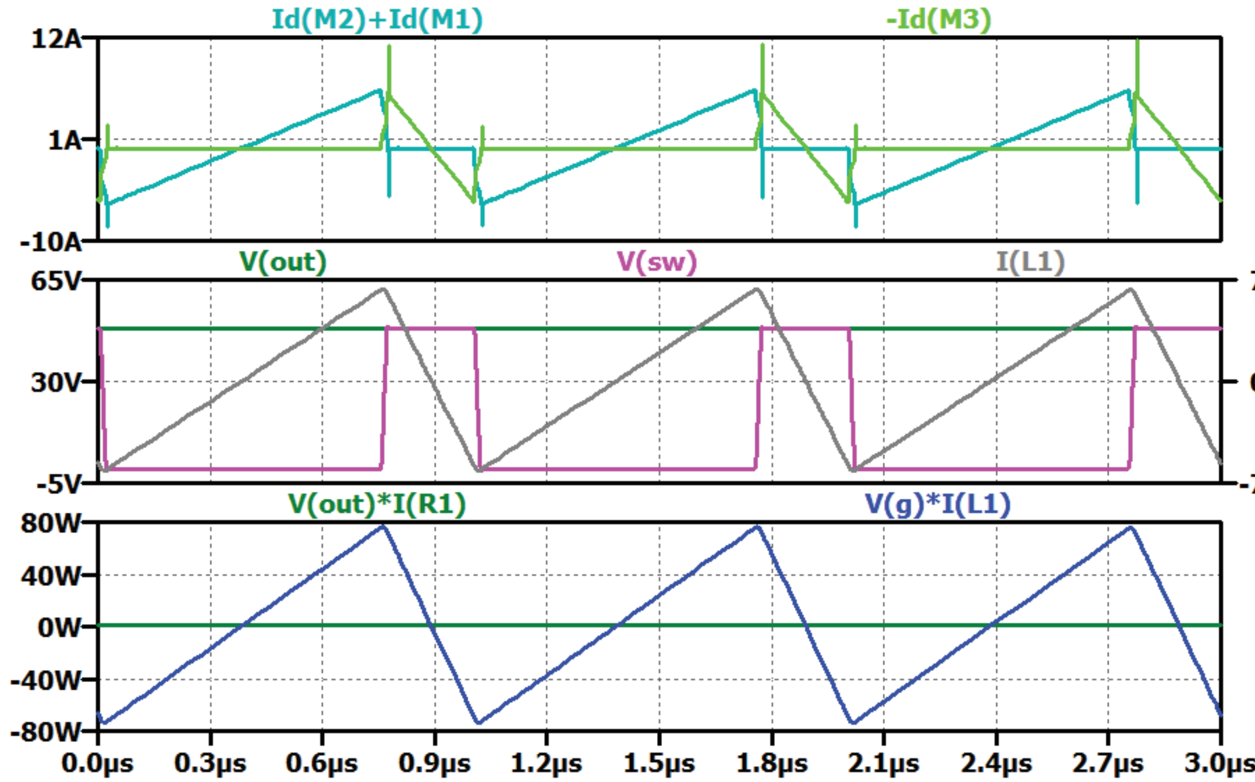





# Switching Transitions

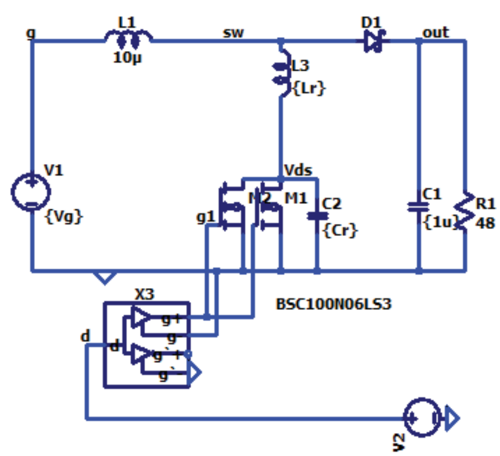


# Low Power Operation



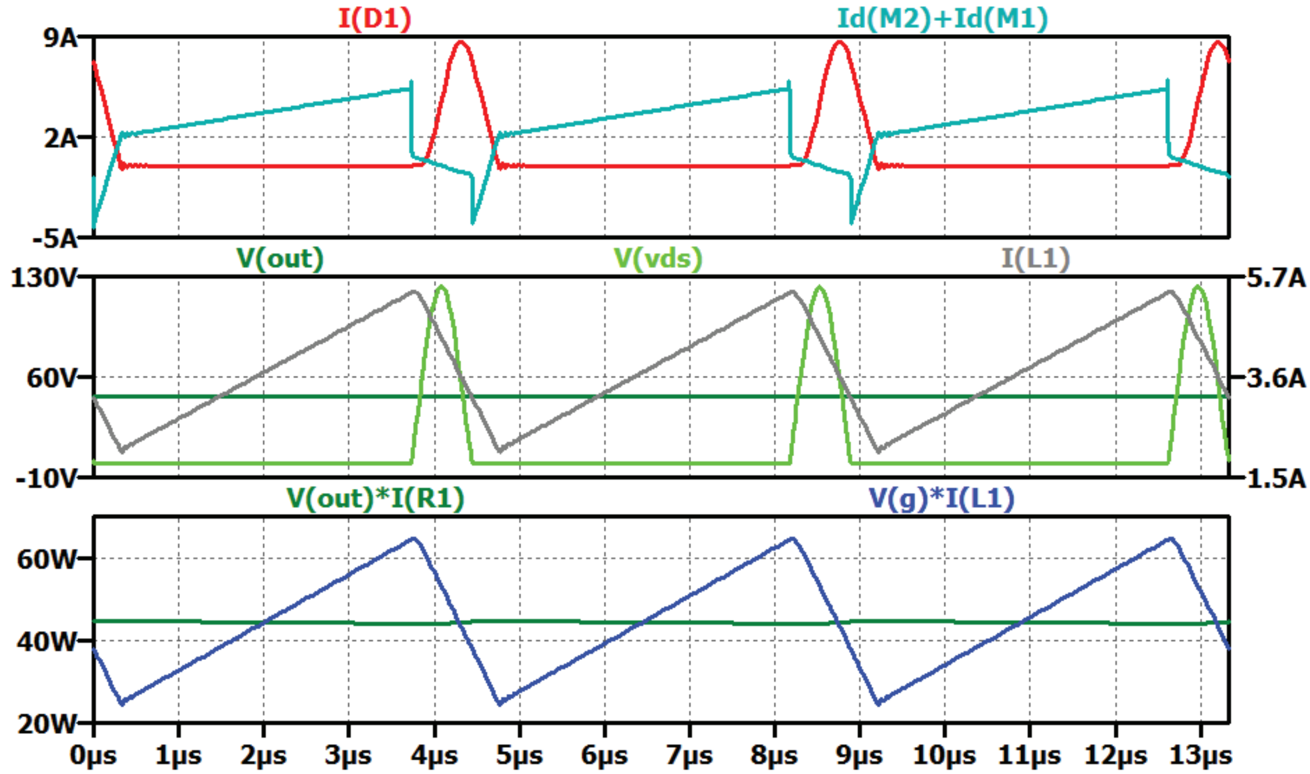



# Resonant Operation



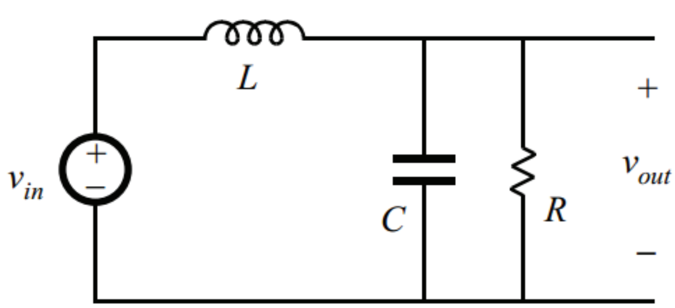

| *Switching* | *L* | $C_{out}$ | $f_s$ | Diode | *η* (Sim) |
|---|---|---|---|---|---|
| Hard | 22uH | 22uF | 202k | Si (FR) | 93.9% |
| Hard | 22uH | 22uF | 202k | Si Schottky | 95.8% |
| Soft | 4.65uH | 22uF | 202k | Si Schottky | 98.4% |
| Soft | 710nH | 4.4uF | 1 MHz | Si Schottky | 98.2% |
| Soft | 710nH | 4.4uF | 1 MHz | MOSFET | 99.6% |
| Resonant | 10uH + 2.4uH | 1uF + 10nF | 225 kHz | Si Schottky | 98.6% |
| Resonant | 10uH + 2.4uH | 1uF + 10nF | 225 kHz | MOSFET | 99.96% |

# Resonant Boost Converter

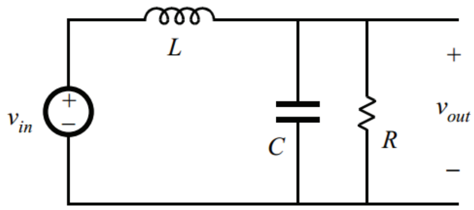


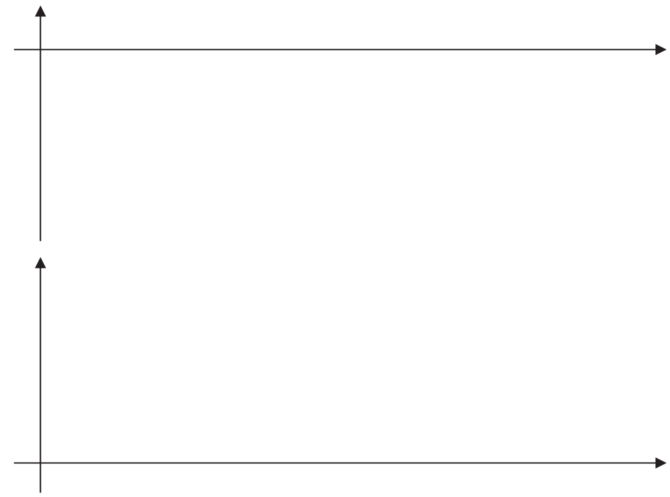



# Resonant Circuits



# Resonant Circuit Analysis



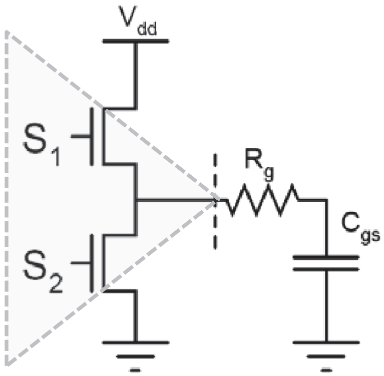



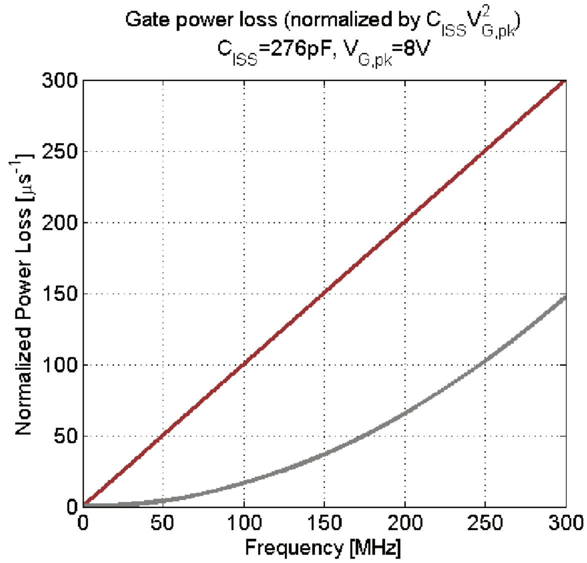


# Soft Switching

- Advantages
  - Reduced switching loss
  - Possible operation at higher switching frequency
  - Lower EMI
- Disadvantages
  - Increased current and/or voltage stresses due to circulating current
  - Higher peak and rms current values
  - Complexity of analysis and modeling

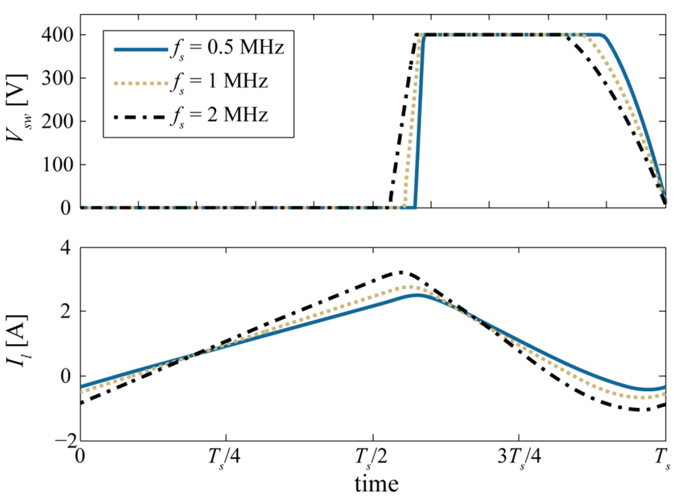
# Limitations: Gate Drive

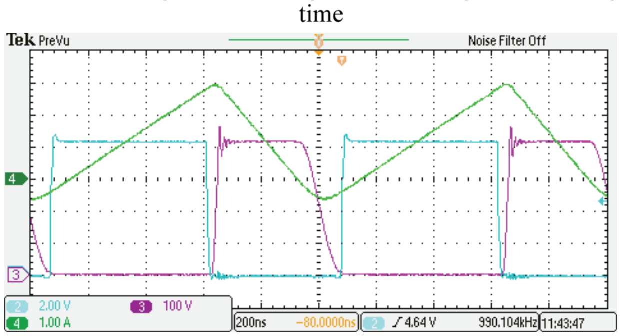





# Limitations: $t_d/T_s$

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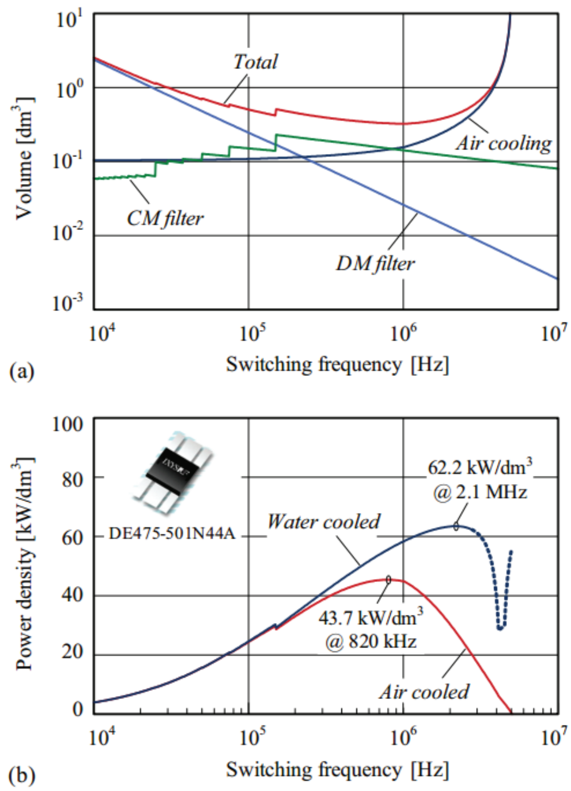
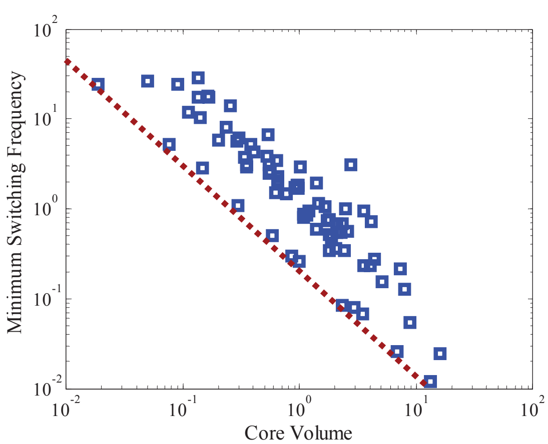
# Limitations: Thermal

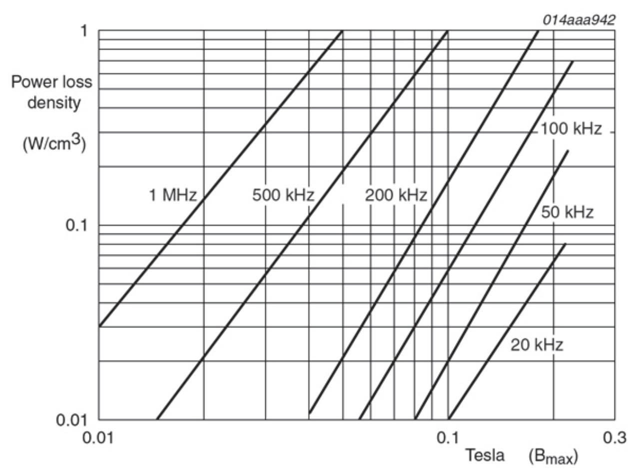



Kolar, J.W.; Drofenik, U.; Biela, J.; Heldwein, M.L.; Ertl, H.; Friedli, T.; Round, S.D.; "PWM Converter Power Density Barriers," *Power Conversion Conference - Nagoya, 2007. PCC '07*, vol., no., pp.P-9,P-29, 2-5 April 2007



# Limitations: Magnetics Design



# Limitations: Circuit Modeling