ECEN 5817 Resonant and Soft-Switching Techniques in Power Electronics

Instructor:

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Prerequisite: ECEN5797 Introduction to Power Electronics

Textbook:

Erickson and Maksimovic, *Fundamentals of Power Electronics,* second edition, Chapters 19 and 20

Extensive supplementary notes and chapters on the course web site

ECEN5817 website: http://ecee.colorado.edu/~ecen5817

Continuously updated through the semester, please plan to check frequently

- Announcements and lecture schedule
- Lecture slides
  - Slides suitable for taking notes posted before the lecture
  - Annotated lecture slides posted after the lecture
- Additional course materials
- Homework assignments and solutions
  - Password protected solutions

Preliminaries

Assignments and exams

- 10-12 week-long homework assignments posted on the course website
- One midterm exam and one final exam, both take home

Policies (see details on the course website)

- Collaboration on HW assignment is allowed
- A blog has been setup to enable all students to exchange questions and comments on the course materials or homework problems; an invitation to contribute to the blog will be e-mailed this week
- Copying someone else's work is not allowed; all work you turn in must be your own
- Absolutely no collaboration in any form allowed on the exams

Grading

- Homework (total) 40%
- Midterm exam 20%
- Final exam 40%

Notes for off-campus students

- Send an e-mail to the instructor at maksimov@colorado.edu to introduce yourself and provide your preferred e-mail address
- Lectures posted on-line by CAETE within 24 hours, often within hours
- Due dates are nominally the same as for on-campus students, *one week* grace period allowed
- To submit your work, scan (b&w, 150 dpi is fine) into a **single easily readable pdf**
    - **Include your name and e-mail address on the front page**
    - Submit online via CU Boulder Desire2Learn (D2L) system
    - Alternative submission methods
        - Email the pdf as attachment to maksimov@colorado.edu
        - Fax to: 303-492-2758, addressed to Dragan Maksimovic, include ECEN5817, your name, hw#, and page number on every page
        - Mail to:

          Dragan Maksimovic
          ECEE Department
          425 UCB
          University of Colorado
          Boulder, CO 80309-0425
- **Keep a copy of your work**

Office hours, questions

Wednesday, 11 am -12pm, Thursday 9-10:30am MT

Office: ECOT 346

Telephone: 303-492-4863

Blog or e-mail questions welcome at any time; will try to answer within 24 hours (M-F)

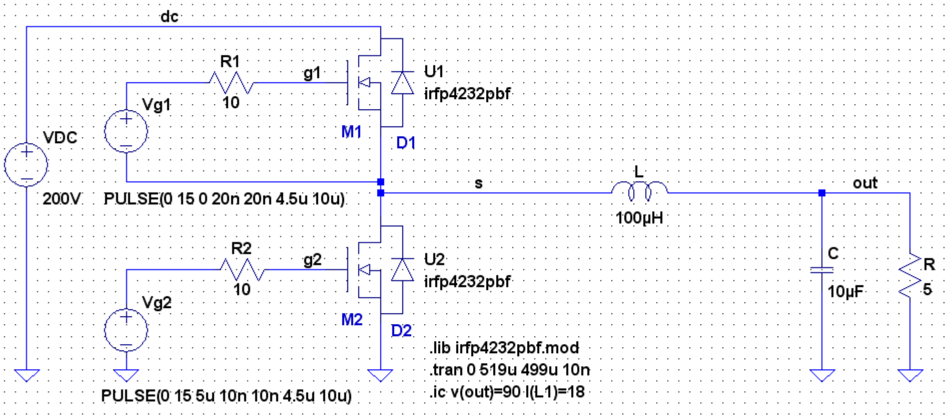
Please use ECEN5817 in the subject line in any course-related emails

Introduction

- **Major power electronics applications: functionality, efficiency, size, cost**
  - Power distribution systems, power supplies for wide range of applications
  - Energy-efficient lighting: electronic ballasts for fluorescent lamps, LED drivers
  - Hybrid and electric vehicles
  - Renewable energy systems: photovoltaic power systems, wind power systems
- **A simple converter example**
  - Standard "hard-switching" operation
  - Resonant circuit basics
  - Switching losses
  - Soft-switching concept, introduction to zero-voltage switching (ZVS) converter operation
  - Introduction to resonant inverter operation
- **Advantages and disadvantages of resonant and soft-switching converters**
- **Course outline**

A Simple Converter Example

- Synchronous buck point-of-load DC-DC converter
- One leg of bridge DC-DC converters
- One leg of single-phase or three-phase DC-AC inverters



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.tran 0 519u 499u 10n
.ic v(out)=90 I(L1)=18
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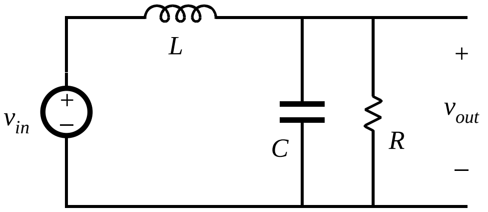
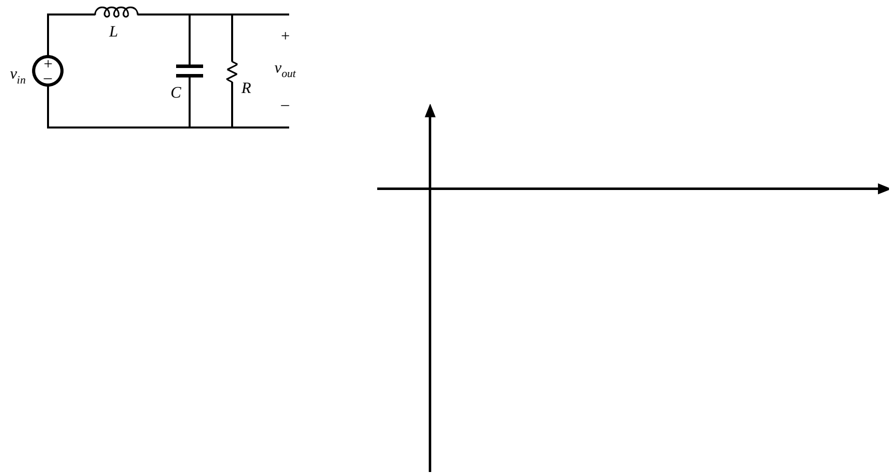
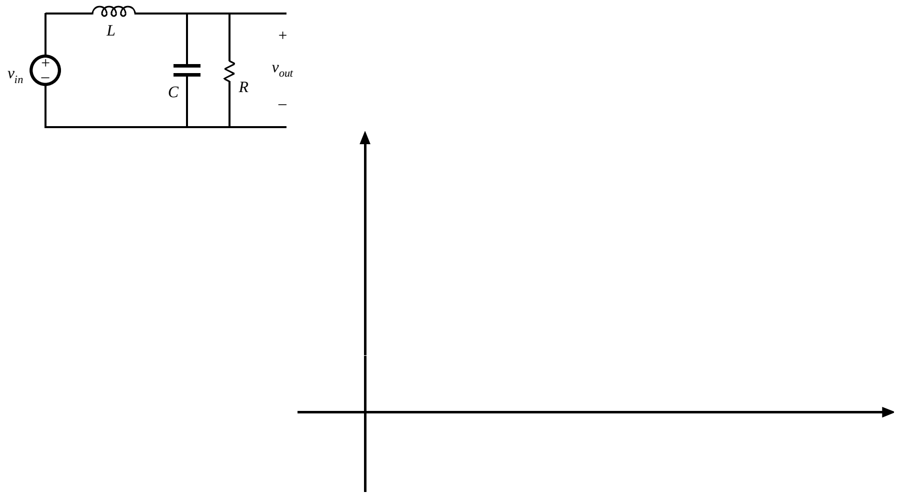
Resonant Circuit Basics



Resonant Circuit: Frequency Response



Resonant Circuit: Time Response

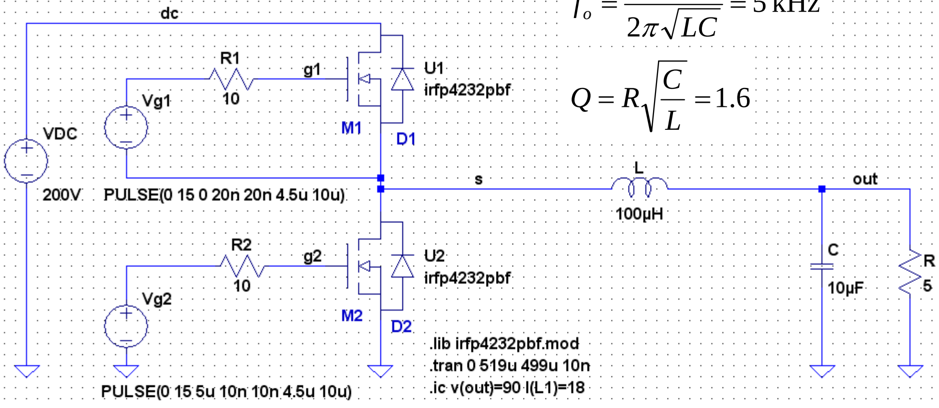


Circuit Example: Standard "Hard-Switched" PWM Operation

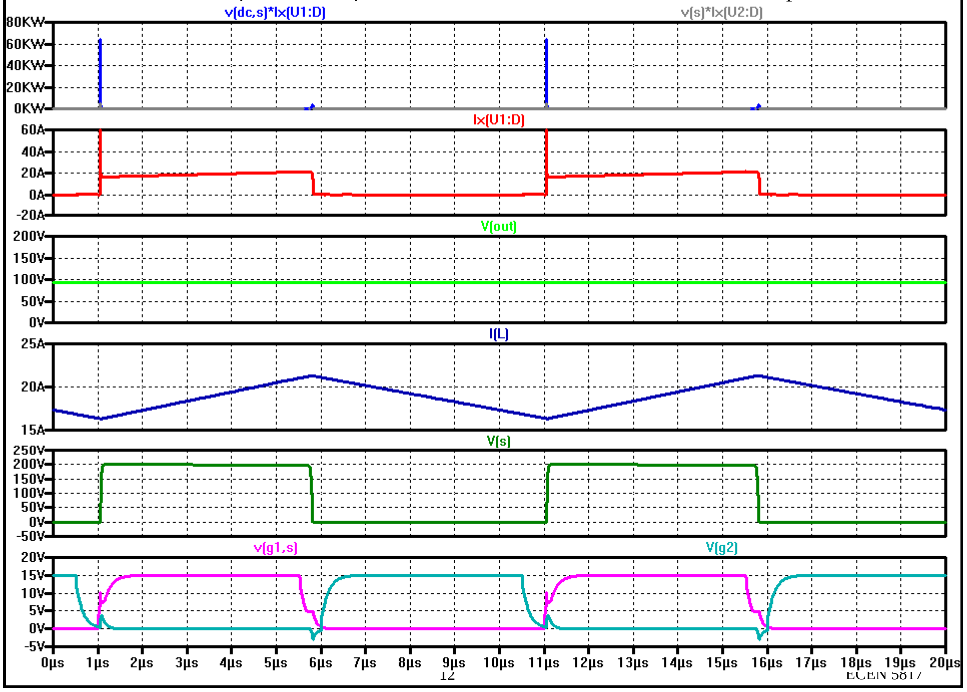
$$f_s = 100\,\text{kHz},\ D \approx 0.5$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 5\,\text{kHz}$$

$$Q = R\sqrt{\frac{C}{L}} = 1.6$$



L = 100 µH, C = 10 µF, R = 5 Ω: standard hard-switched PWM operation



Switching losses

- Energy is lost during the semiconductor switching transitions, via several mechanisms:
  - Transistor switching times
  - Diode stored charge
  - Energy stored in device capacitances and parasitic inductances
- Semiconductor devices are *charge controlled* – controlling charge must be inserted or removed to switch a device

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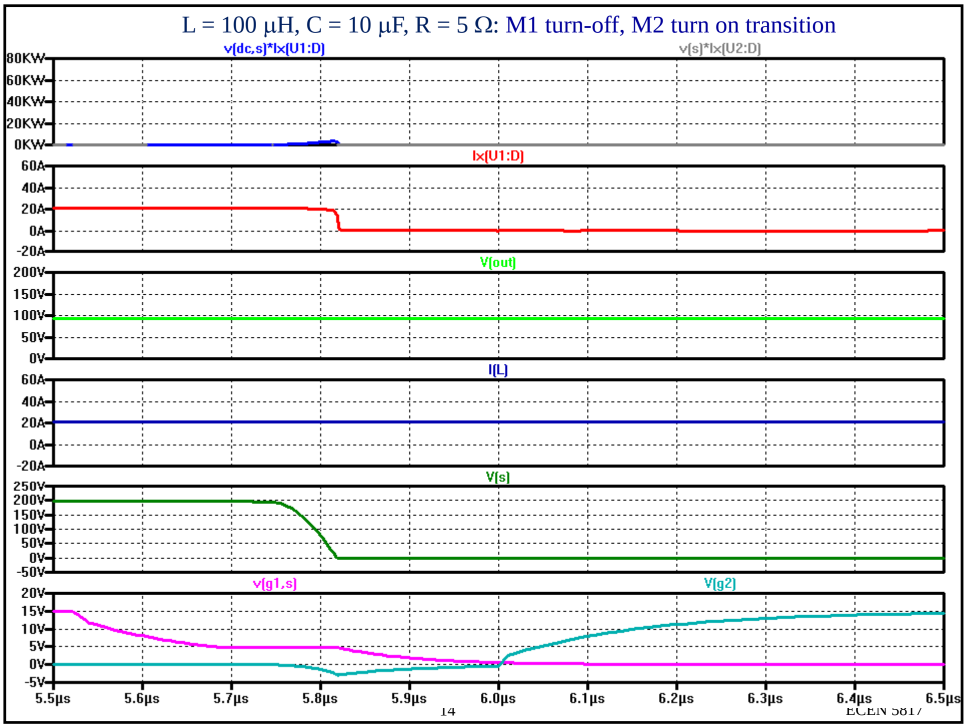
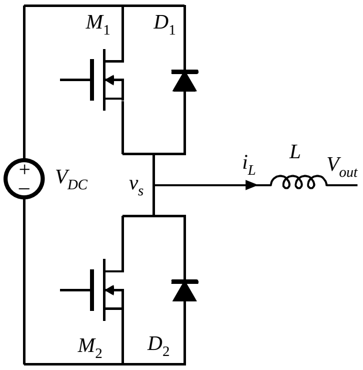
L = 100 μH, C = 10 μF, R = 5 Ω: M1 turn-off, M2 turn on transition

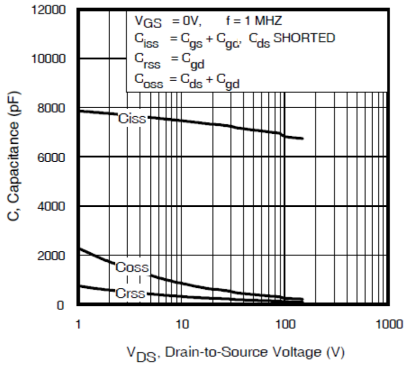


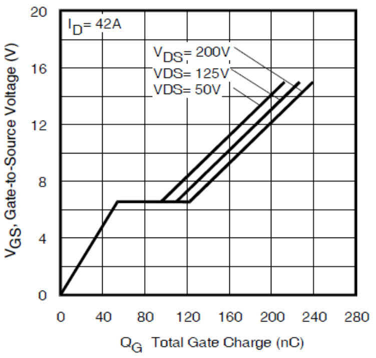
M1 turn-off, M2 turn-on transition



Device capacitances

irfp4232 example





Transistor switching times

MOSFET

- Majority carrier device
- Turn-on and turn-off delays as well as current rise/fall times are in the order of several tens of nanoseconds
- At turn off, device output capacitance slows down v_{ds} voltage increase
- No significant energy loss during MOSFET turn-off transition, even if current prior to turn-off is not zero; device capacitance is charged up

IGBT

- Conduction through built in bipolar transistor, a minority-carrier device; base charge must be removed at turn-off ("current tail" observed at turn-off)
- Turn-on/turn-off times in the hundreds of nanoseconds
- If current prior to turn-off is not zero, energy loss during turn off can be significant

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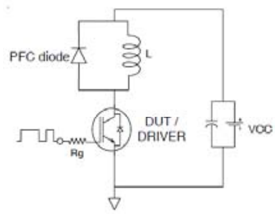
Transistor switching speed and turn-off transition: IGBT example



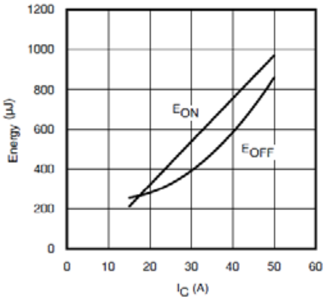
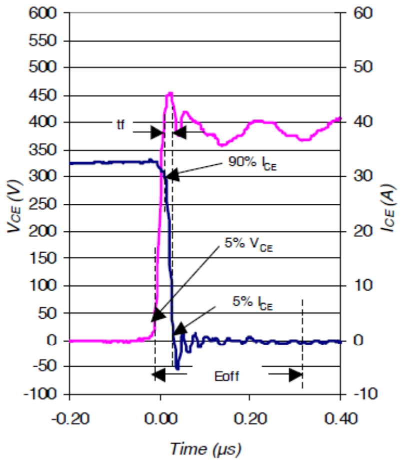
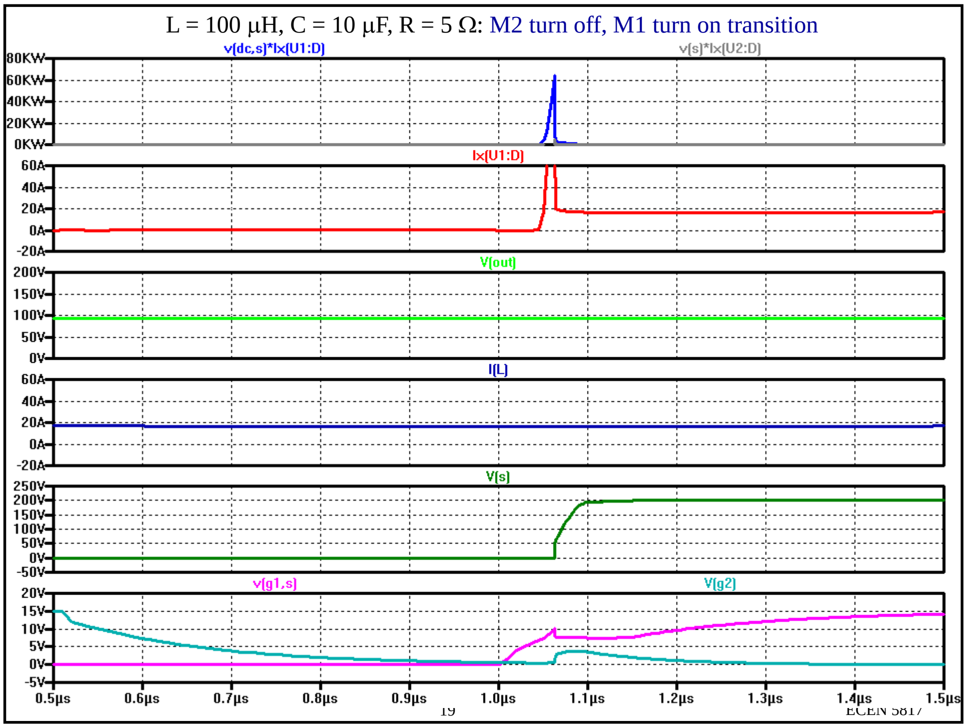


Fig. 11 - Typ. Energy Loss vs. I_C
$T_J = 125°C$; $L = 200\mu H$; $V_{CE} = 390V$, $R_G = 3.3\Omega$; $V_{GE} = 15V$.
Diode clamp used: 30ETH06 (See C.T.3)

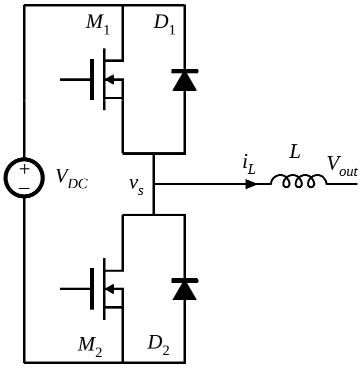


IRGP50B60 (IGBT+diode)

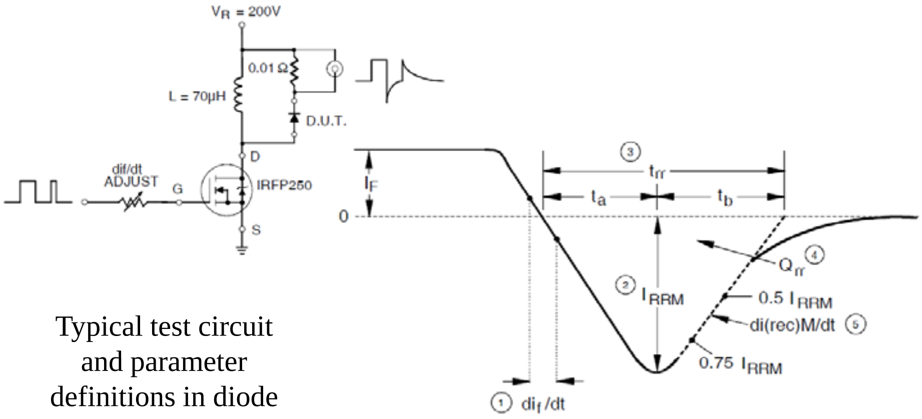
L = 100 μH, C = 10 μF, R = 5 Ω: M2 turn off, M1 turn on transition



Hard-switched: M2 turn-off, M1 turn-on transition



Diode Stored Charge and Reverse Recovery



Typical test circuit and parameter definitions in diode data sheets

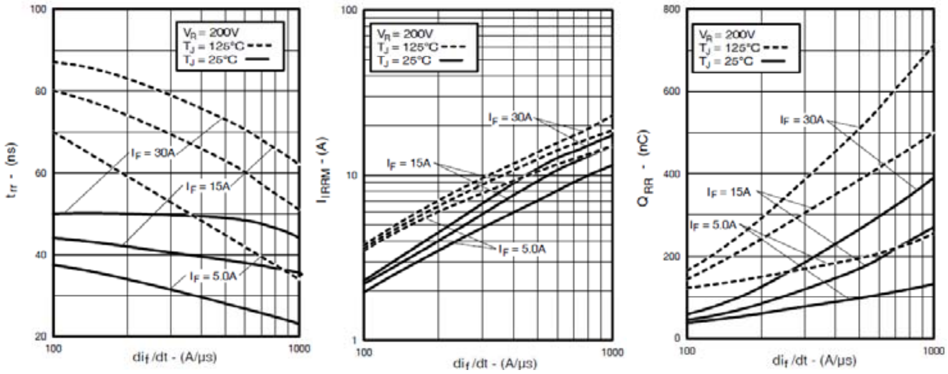
1. di_f/dt - Rate of change of current through zero crossing
2. I_{RRM} - Peak reverse recovery current
3. trr - Reverse recovery time measured from zero crossing point of negative going I_F to point where a line passing through 0.75 I_{RRM} and 0.50 I_{RRM} extrapolated to zero current
4. Q_{rr} - Area under curve defined by t_{rr} and I_{RRM}

$$Q_{rr} = \frac{t_{rr} \times I_{RRM}}{2}$$

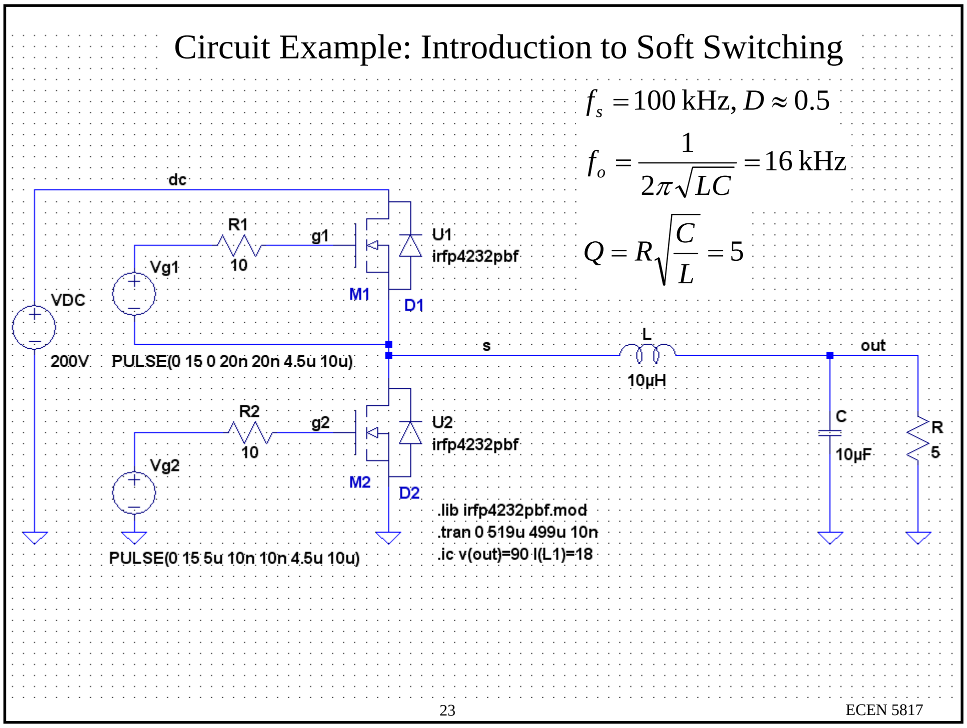
5. $di_{(rec)M}/dt$ - Peak rate of change of current during t_b portion of t_{rr}

Example

Diode in IRGP50B60 (IGBT+diode): ultra-fast, “soft recovery”



Reverse recovery time t_{rr}, maximum reverse recovery current I_{RRM}, and reverse recovery charge Q_{rr} depend on diode forward current I_F prior to turn off, rate of current decay di_f/dt, and junction temperature T_J



Circuit Example: Introduction to Soft Switching

$$f_s = 100\,\text{kHz}, D \approx 0.5$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 16\,\text{kHz}$$

$$Q = R\sqrt{\frac{C}{L}} = 5$$

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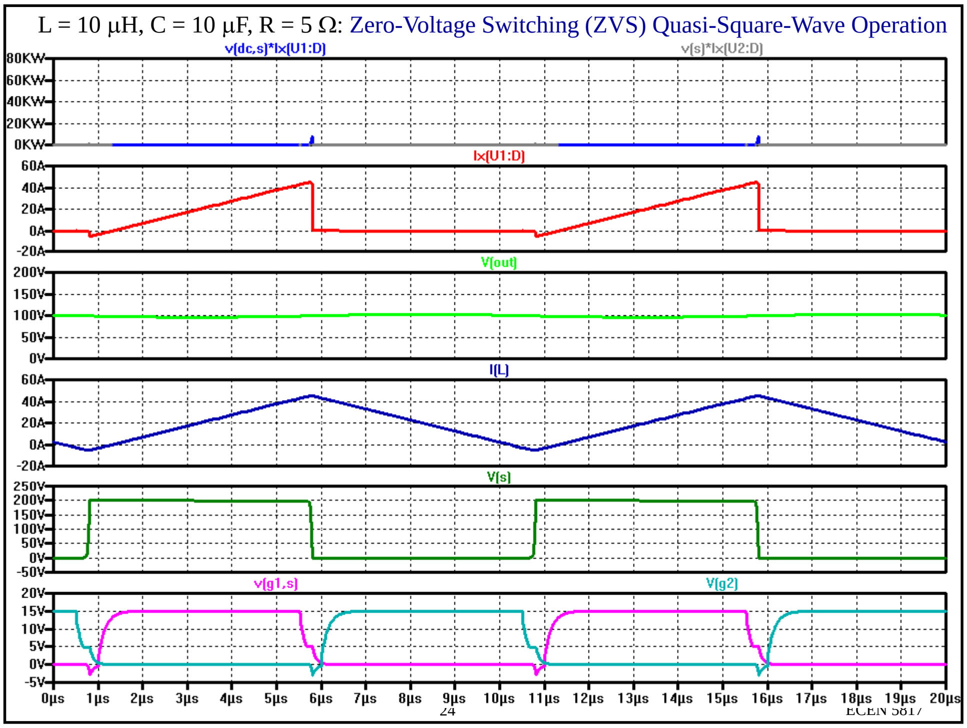
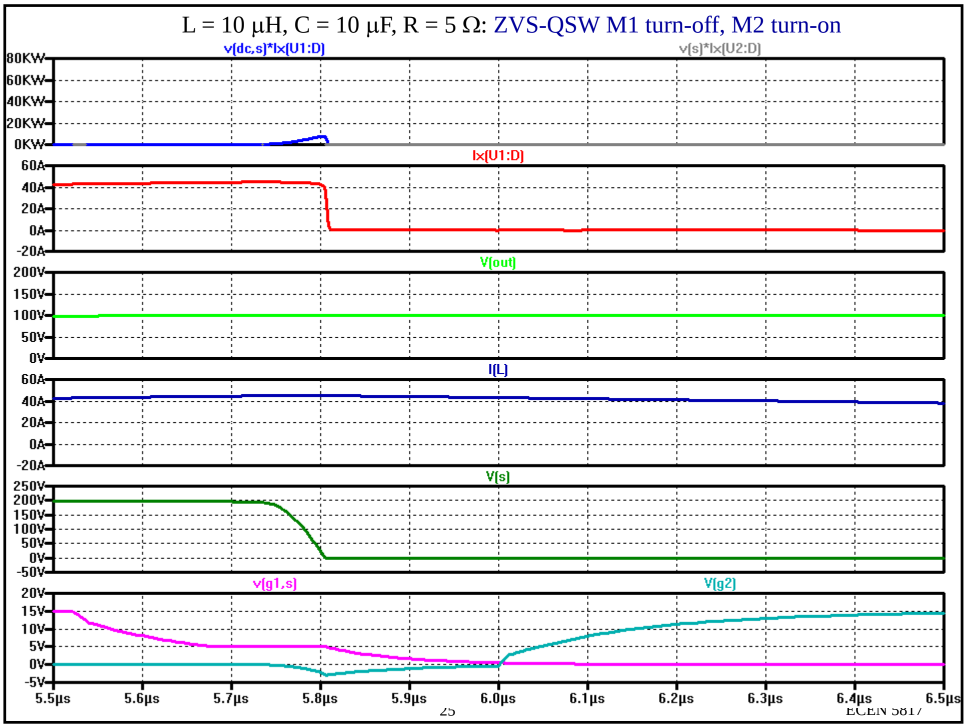
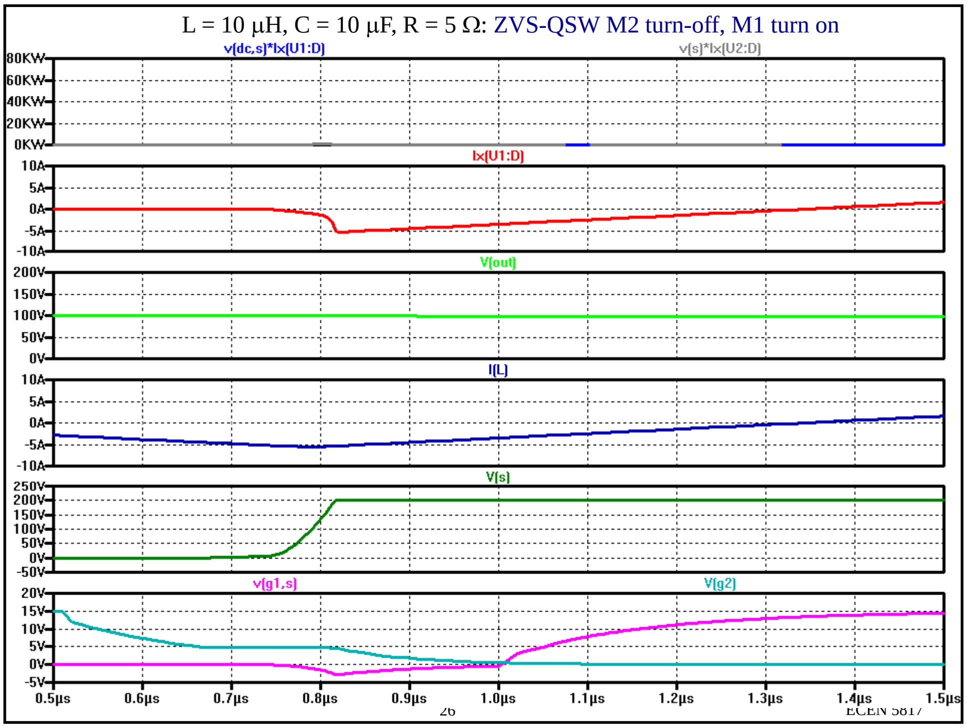
.tran 0 519u 499u 10n
.ic v(out)=90 I(L1)=18



L = 10 µH, C = 10 µF, R = 5 Ω: Zero-Voltage Switching (ZVS) Quasi-Square-Wave Operation

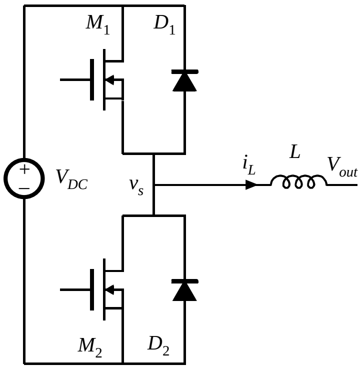


L = 10 μH, C = 10 μF, R = 5 Ω: ZVS-QSW M1 turn-off, M2 turn-on



L = 10 μH, C = 10 μF, R = 5 Ω: ZVS-QSW M2 turn-off, M1 turn on

ZVS-QSW: M2 turn-off, M1 turn-on transition

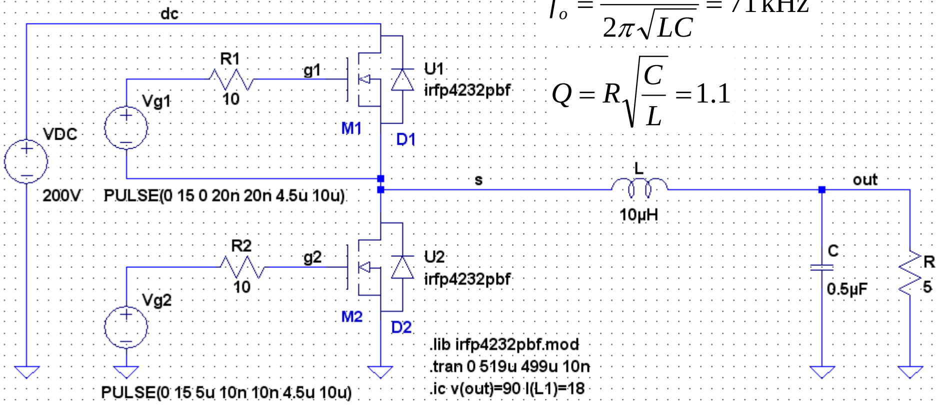


Circuit Example: Introduction to Resonant Converters

$$f_s = 100\,\text{kHz}, D \approx 0.5$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 71\,\text{kHz}$$

$$Q = R\sqrt{\frac{C}{L}} = 1.1$$



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.lib irfp4232pbf.mod
.tran 0 519u 499u 10n
.ic v(out)=90 I(L1)=18
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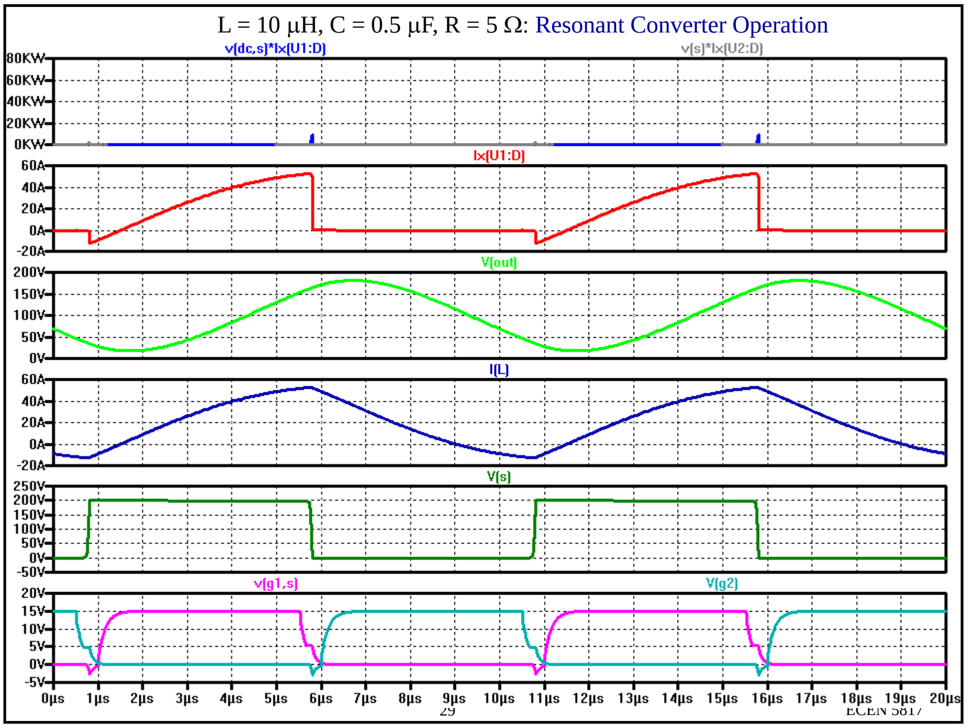
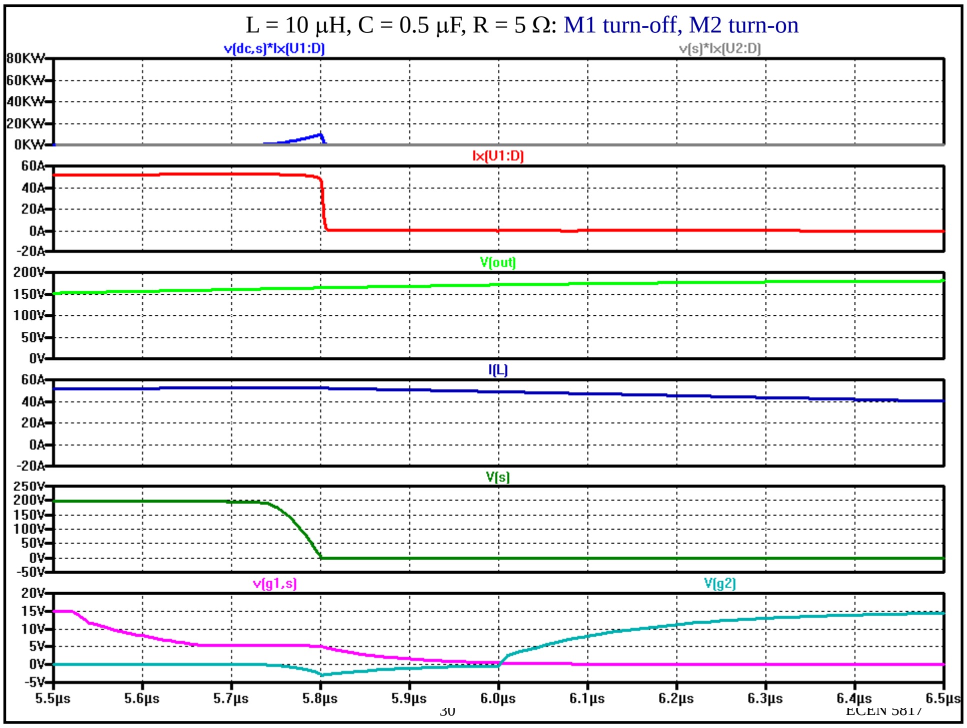
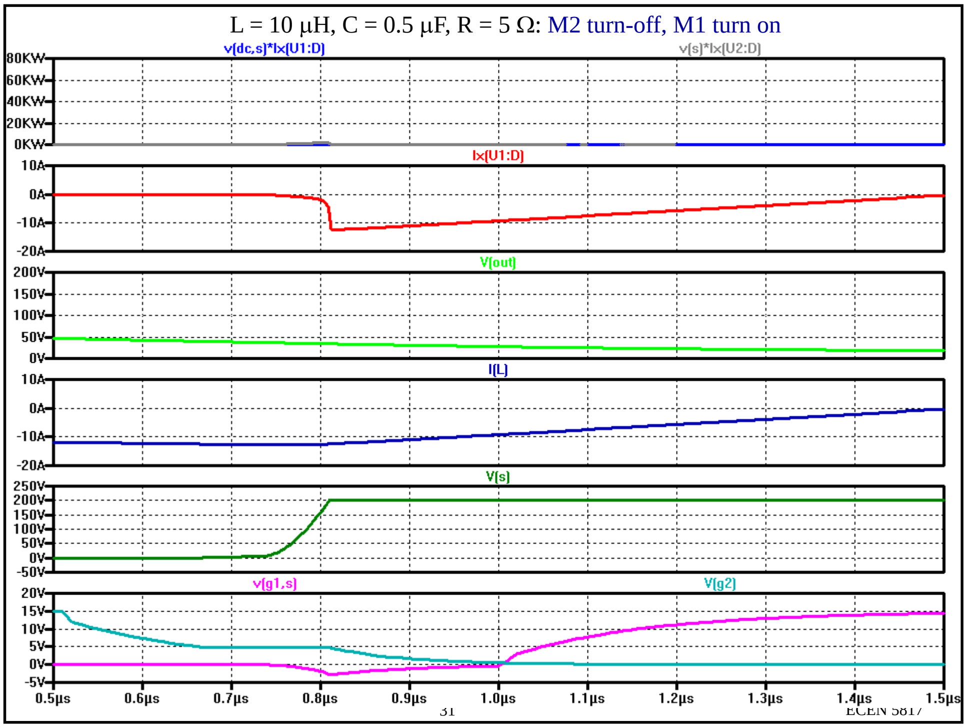
L = 10 μH, C = 0.5 μF, R = 5 Ω: Resonant Converter Operation



L = 10 μH, C = 0.5 μF, R = 5 Ω: M1 turn-off, M2 turn-on



L = 10 µH, C = 0.5 µF, R = 5 Ω: M2 turn-off, M1 turn on



Comparison of Losses

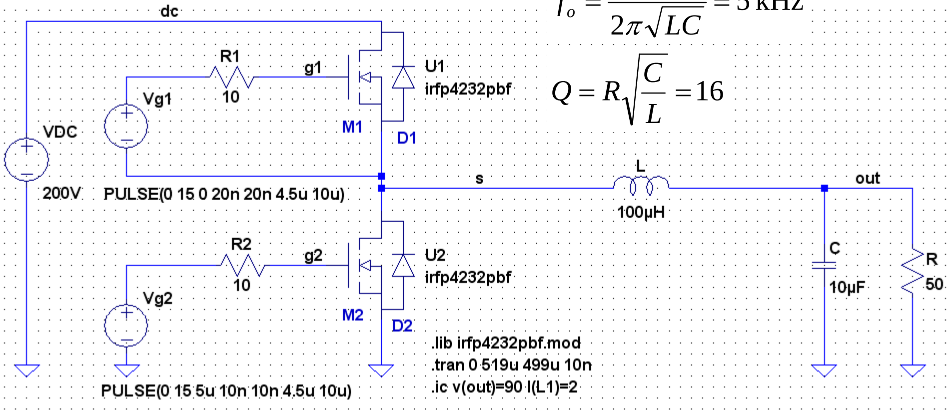
	Load R = 5 Ω		
	Hard-switching PWM L = 100 µH, C = 10 µF	ZVS QSW L = 10 µH, C = 10 µF	Parallel resonant inverter L = 10 µH, C = 0.5 µF
P_{loss} (U1) [W]	57.5	34.3	45.9
P_{loss} (U2) [W]	6.1	8.6	12.0
$P_{loss,\ total}$ [W]	**63.6**	42.9	57.9
P_{out} [W]	1750	1970	2610
η [%]	96.5	97.9	97.8

Same Example: Light-Load Operation

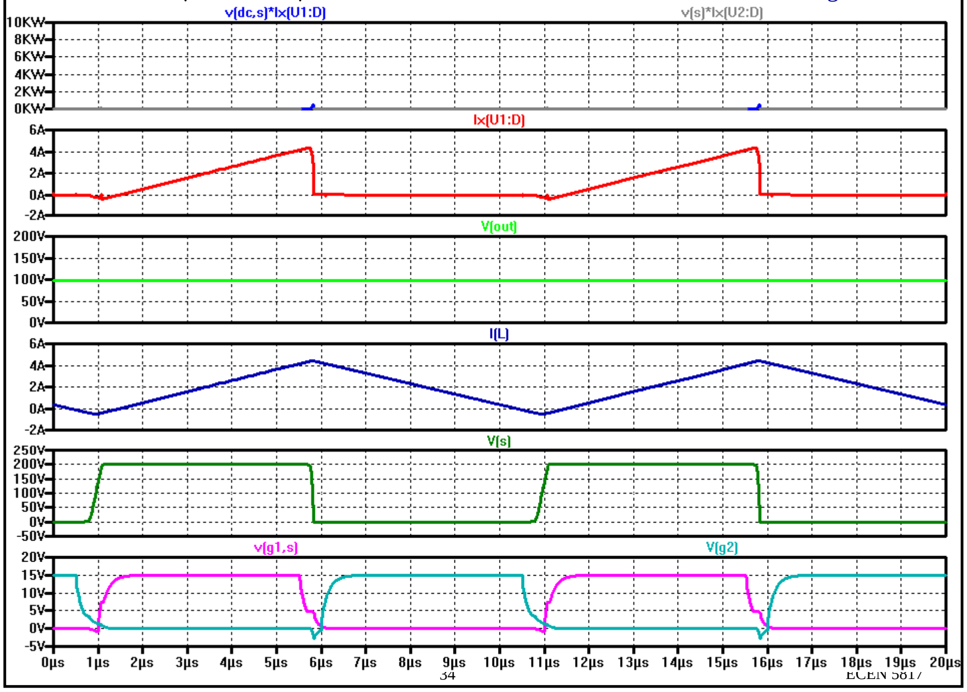
$$f_s = 100\,\text{kHz},\ D \approx 0.5$$

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 5\,\text{kHz}$$

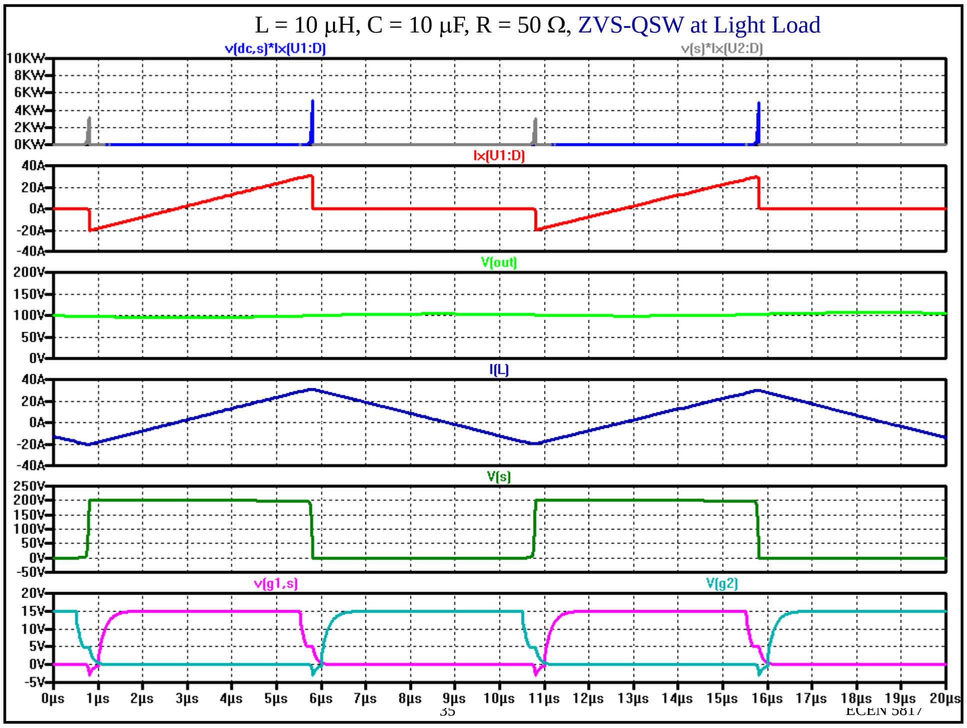
$$Q = R\sqrt{\frac{C}{L}} = 16$$



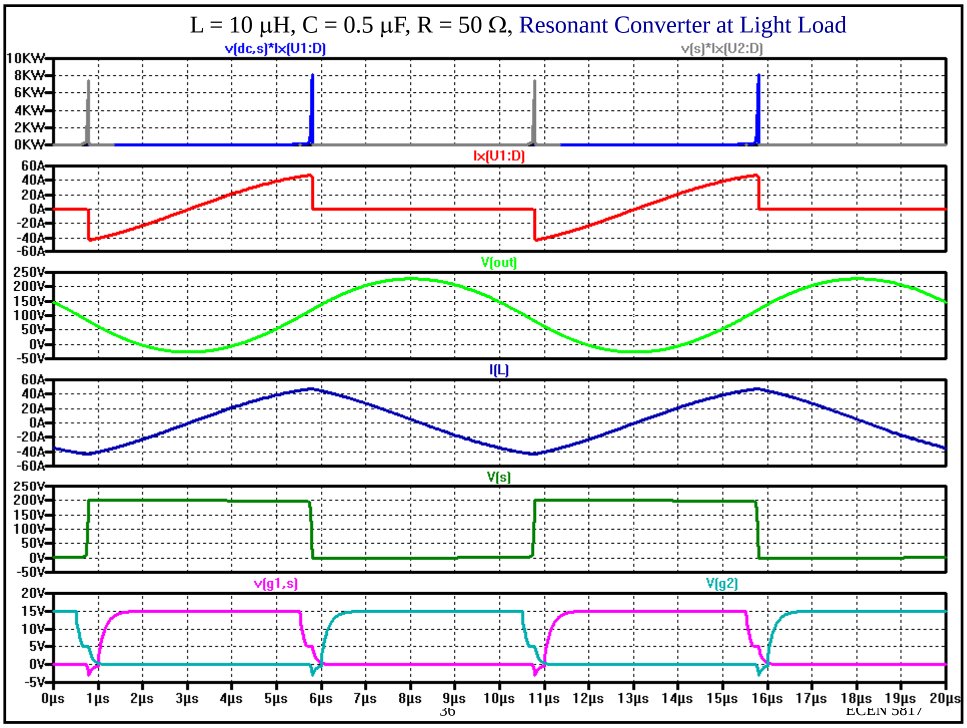
L = 100 µH, C = 10 µF, R = 50 Ω: Standard Hard-Switched Converter at Light Load



L = 10 μH, C = 10 μF, R = 50 Ω, ZVS-QSW at Light Load



L = 10 μH, C = 0.5 μF, R = 50 Ω, Resonant Converter at Light Load



Comparison of Losses

	Load R = 5 Ω		
	Hard-switching PWM L = 100 µH, C = 10 µF	ZVS QSW L = 10 µH, C = 10 µF	Parallel resonant L = 10 µH, C = 0.5 µF
P_{loss} (U1) [W]	57.5	34.3	45.9
P_{loss} (U2) [W]	6.1	8.6	12.0
$P_{loss,\ total}$ [W]	**63.6**	42.9	57.9
P_{out} [W]	1750	1970	2610
h [%]	96.5	97.9	97.8

	Load R = 50 Ω		
	Hard-switching PWM L = 100 µH, C = 10 µF	ZVS QSW L = 10 µH, C = 10 µF	Parallel resonant L = 10 µH, C = 0.5 µF
P_{loss} (U1) [W]	1.3	20.2	37.5
P_{loss} (U2) [W]	0.2	13.9	34.3
$P_{loss,\ total}$ [W]	7.4	34.1	**71.8**
P_{out} [W]	188	203	369
η [%]	99.2	85.6	83.7

Resonant and soft-switching conversion: advantages

Reduced switching loss

- *Zero-current switching*: switch current is zero prior to turn off
- *Zero-voltage switching*: switch voltage is zero prior to turn on

Possible operation at higher switching frequency, may enable reduced size of passive components, higher power density

Zero-voltage switching also reduces converter-generated EMI

In specialized applications, resonant networks may be unavoidable

- Resonant inverters in electronic ballasts for gas-discharge lamps, other high-frequency ac applications
- High voltage converters: significant transformer leakage inductance and winding capacitance leads to resonant network

Resonant conversion: disadvantages

Can optimize performance at one operating point, but in most cases not over wide range of input voltage or load power variations

Significant currents may circulate through the tank elements, even when the load is reduced, leading to poor efficiency at light load

Quasi-sinusoidal waveforms exhibit higher peak and RMS values than equivalent rectangular waveforms

All of the above lead to increased conduction losses, which can offset the reduction in switching loss

Variable frequency operation may be required

Complexity: *need different analysis and modeling methods*

Applications of resonant and soft-switching converters

High-frequency ac inverter applications

- Electronic ballasts for gas-discharge lamps
- Electrosurgical generators
- Induction heaters
- Piezoelectric transformers

Efficiency improvements

- Mitigation of switching losses caused by diode stored charge in PFC rectifiers
- Mitigation of switching losses due to leakage inductance in isolated DC-DC converters
- Mitigation of switching losses due to current tailing and diode reverse recovery in IGBT-based DC-DC converters and DC-AC inverters

High-frequency high-density dc–dc converters

- Reduced switching loss, improved efficiency, higher-frequency operation

High-voltage and other specialized converters

- Transformer non-idealities incorporated into resonant tanks

Course Outline

1. **Analysis of resonant converters using the sinusoidal approximation**
   - Classical series, parallel, LCC, and other topologies
   - Modeling based on sinusoidal approximation
   - Zero voltage and zero current switching concepts
   - Resonant converter design techniques based on frequency response
2. **Sinusoidal analysis: small-signal ac behavior with frequency modulation**
   - Spectra and envelope response
   - Phasor transform method
3. **State-plane analysis of resonant converters**
   - Fundamentals of state-plane and averaged modeling of resonant circuits
   - Exact analysis of the series and parallel resonant dc-dc converters

Course Outline

4. **Configurations and state plane analysis of soft-switching converters**
   - Quasi-resonant (resonant-switch) topologies
   - Quasi-square wave converters
   - Soft switching in forward and flyback converters
   - Zero voltage transition converter
   - DC-DC converter with fixed conversion ratio (“DC transformer”)
5. **Energy-Efficiency and Renewable Energy Applications (time-permitting)**
   - Computer server power distribution, efficiency optimization techniques
   - Soft-switching techniques for improved efficiency in DC-AC inverters

Assignments

Reading assignments:
Section 19.1, *Sinusoidal analysis of resonant converters*
Section 19.2, *Examples*

HW1 has been posted