6.334 Power Electronics
Spring 2007

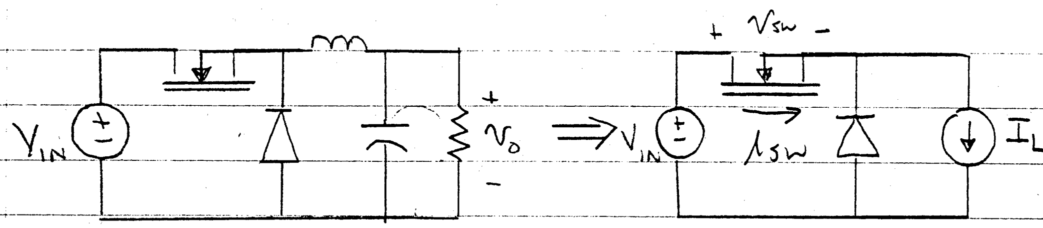
Power Electronics Notes – D. Perreault

Notes: Reading KS+V Chapter 24

★★ Switching Losses and snubbers

★ Semiconductor Losses (Back of the Envelope)

Example: Buck converter w/ MOSFET

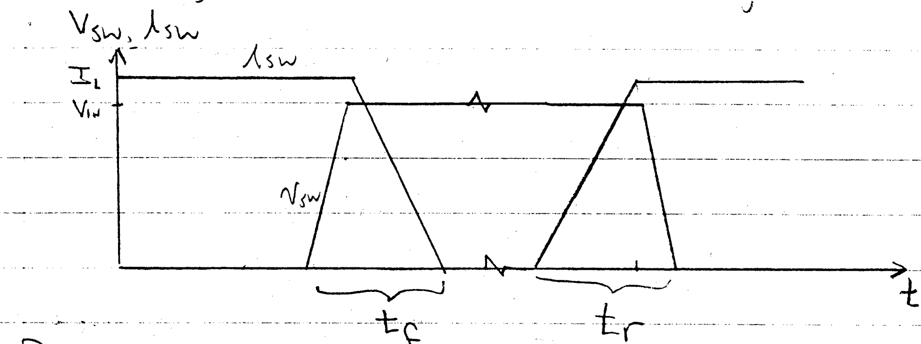


Conduction losses

Fet (resistive) $P_{FET,COND} = i_{RMS}^2 R_{ds,on} \cong (I_L^2 D) R_{ds,on}$

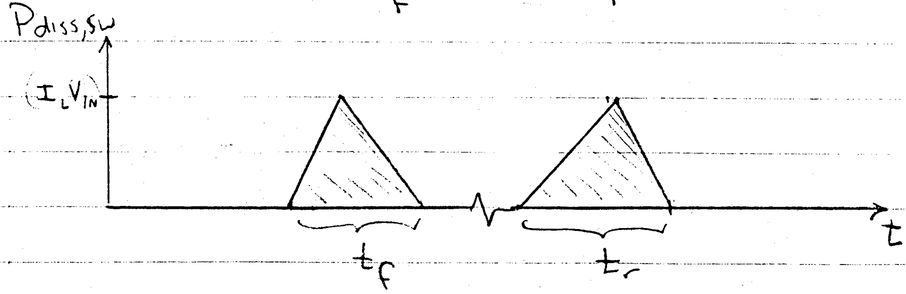
Diode (const drop) $P_{d,cond} = \langle i_{diode} \rangle V_{d,on} \cong (I_L D') V_{d,on}$

Switching Losses (Zoom in on switching) → back of the envelope only!



Turn off of FET: current falls After voltage rises (diode must turn on before sw. current falls)

t_f governed by device params + gate drive



Turn on of Fet: current rises before voltage falls (diode must conduct until switch carries whole current)

t_r governed by device params + gate drive

Linear transitions are a rough approximation!

⇒ other losses (e.g. diode rev. recov.) also exist

$$P_{switch,sw} \cong \left(\tfrac{1}{2} t_f V_{IN} I_L + \tfrac{1}{2} t_r V_{IN} I_L\right) f$$
$$= \tfrac{1}{2} V_{IN} I_L (t_f + t_r) f$$

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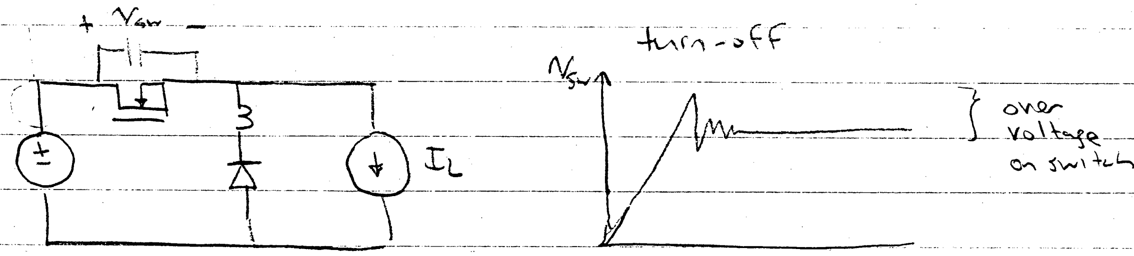
⇒ major switching loss component ∝ f. we want f ↑ so L, C size ↓ but losses limit us.

Other Issues

- we want to switch fast (↓ t_f, t_r) but other factors exist:

→ Parasitics + Overshoots



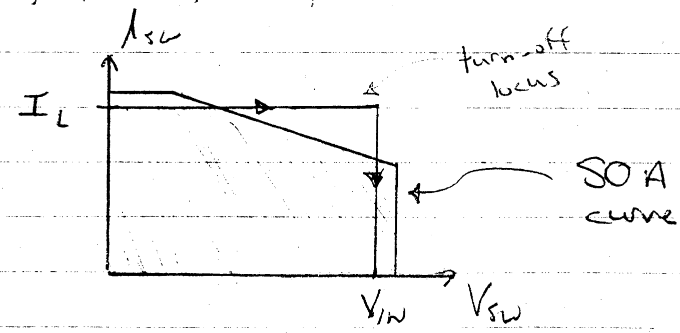
→ EMI

high $\frac{di}{dt}$, $\frac{dv}{dt}$ lead to EMI, + affects control circuits
($\frac{dv}{dt}$ → capacitive coupling, $\frac{di}{dt}$ → inductive coupling)

→ Safe Operating Area

Some devices have limitations on simultaneous voltage + current applied instantaneously (BJT's, GTO's, MCT's)

Can operate at I_L and can operate at V_{IN}, but NOT AT SAME TIME



→ Also, some devices have $\frac{di}{dt}$ or $\frac{dV}{dt}$ limits (esp. thyristor type devices

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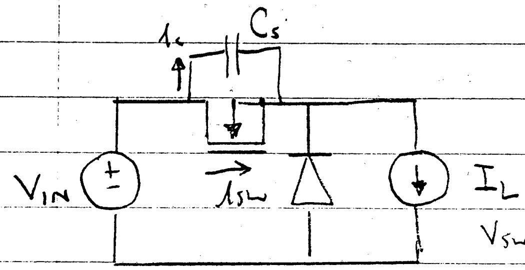
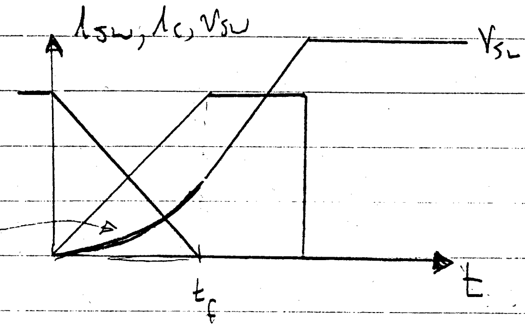
★ **Snubbers**:
1.) Control switching Locus
2.) Lower the 'internal device dissipation

If capacitor across device during turn-off

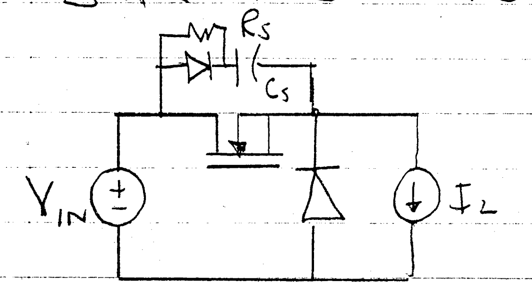


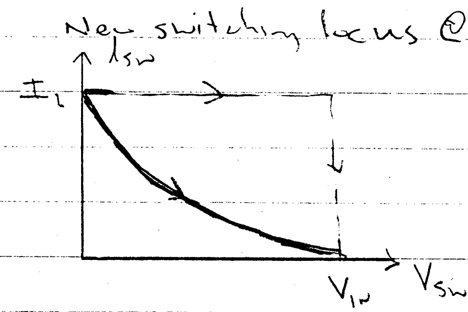


I_L diverted through C_s while switch turns off.
reduced V-rise across switch during turn off → Lower switch losses

★ BUT there will be a big problem when the switch turns on!!

∴ Simple RCD turn off snubber





During turn-off, same as above
As calculated on the next page: $W_{Turn\text{-}off, SW} \cong \frac{I_L^2 t_f^2}{24 C_s}$

During turn on, dissipate C_s energy in R_s $W_{R_S} \cong \frac{1}{2} C_S V_{IN}^2$
(Note: Need a min duty ratio to do this!)

Snubber reduces device switching loss, but increases total dissipation. (typically; this depends on device capacitance)
→ definitely more diss. if device capacitance exceeds "natural" capacitance

To size snubber, trade, P_{device}, P_{R_S}, $\frac{dV}{dt}$ ~~SOA~~, min duty cycle.

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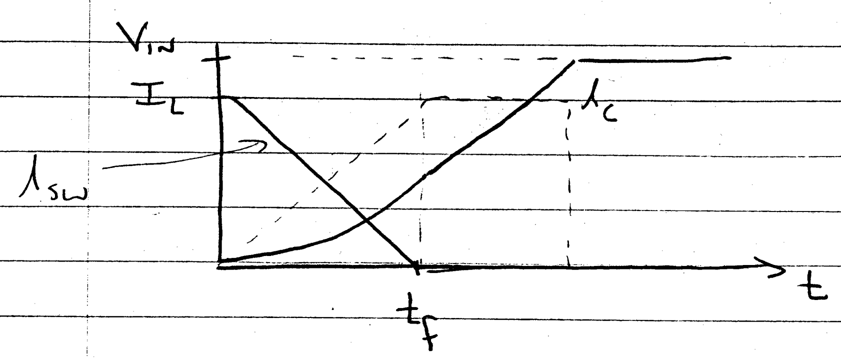


The turn-off loss + capacitor charging can be calculated as follows:

$$i_{SW}(t) = I_L(1 - t/t_f) \qquad 0 < t < t_f$$

$$i_C = I_L(t/t_f) \qquad 0 < t < t_f$$

$$V_{SW} = \frac{1}{C}\int_0^t i_C(t)\,d\tau = \frac{I_L}{2Ct_f}t^2 \qquad 0 < t < t_f$$

$$\therefore E_{SW,OFF} = \int_0^{t_f} V_{SW} i_{SW}\,dt = \int_0^{t_f} \frac{I_L^2}{2Ct_f}\left(t^2 - \frac{t^3}{t_f}\right)dt$$

$$= \frac{I_L^2}{6C}t_f^2 - \frac{I_L^2}{8C}t_f^2$$

$$\boxed{E_{SW,OFF} = \frac{I_L^2 t_f^2}{24C}}$$

With no capacitance, we would get $E_{loss} = \frac{1}{2} I_L V_{IN} t_f$

V_{pk} @ sw. turn off $\frac{I_L}{2C}t_f$ (assumed $< V_{IN}$)

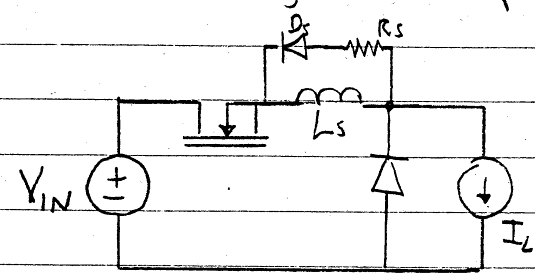
E_{STORED} (in capacitor) $= \frac{1}{2} C V_{IN}^2$

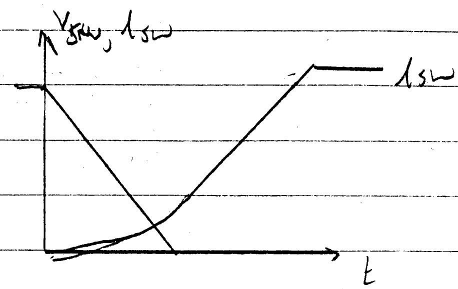
This is $\geq \frac{1}{2} C \frac{I_L^2 t_f^2}{4C^2} = \frac{I_L^2 t_f^2}{8C}$

(V_{pk}^2 @ sw. off point)

$\therefore$ The stored energy in C is much larger than the switch transition loss.

Similar snubbing can be implemented for turn on





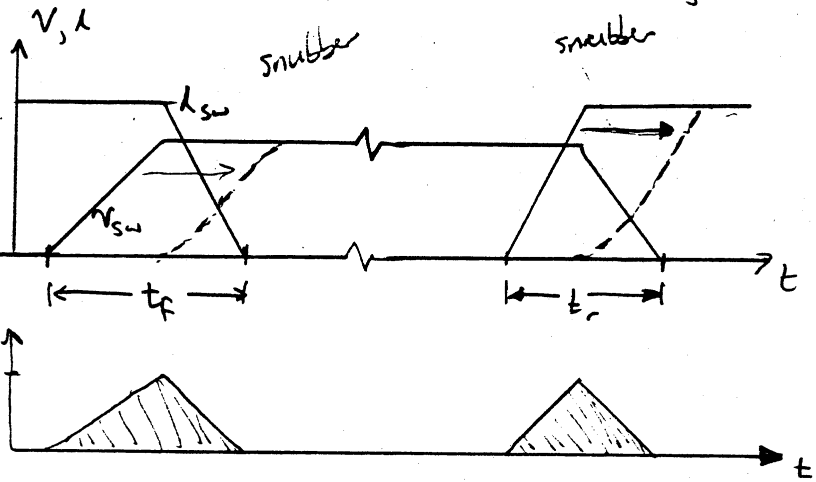
→ reduced switch, diode loss
→ increased total loss (incl. R_s)
→ controlled switching locus (SOA, $\frac{di}{dt}$)

* Note: Snubber reset implies max duty ratio <u>and</u> imposes an overvoltage on the switch!!!

ZCS / ZVS Techniques, dc-dc converter applications

REVIEW: (put initial stuff on board before class)

The switching transitions in conventional PWM converters generate losses due to the nature of the V, i waveforms during the transitions.



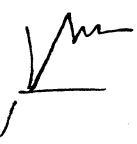
Turn off: V rises 1st (diode on), i falls 2nd

Turn on: i rises 1st (diode on), V falls 2nd

effects

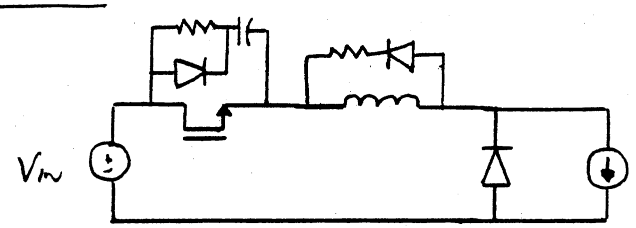
This has 3 deleterious effects:

1. Achievable f_{sw} & efficiency limited
2. EMI due to fast di/dt, dV/dt ⇒ NOISE
3. Switching locus may exceed SOA



LAST TIME: SNUBBERS MITIGATE THESE EFFECTS, BUT ADD LOSSES

e.g.



Today: Soft-Switching techniques try to mitigate these effects without adding substantial losses.

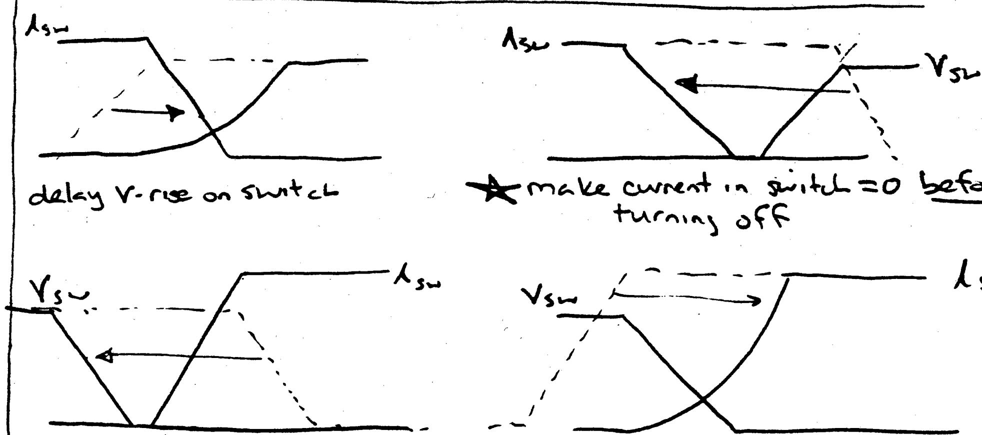
GENERAL METHODS: Zero-Voltage Switching (ZVS)
Zero-Current Switching (ZCS)

Can be applied to both turn-on and turn-off

These techniques typically require additional circuitry &/or control complexity &/or additional conduction losses. But, the trade may be worth it...

Soft switching

	ZERO VOLTAGE	ZERO CURRENT
TURN OFF	★ delay V-rise on switch	★ make current in switch = 0 before turning off
TURN ON	★ make V across switch = 0 before turning on.	★ delay current rise through switch



⇒ The turn-off snubber from before acts like ZVS turn off (in limit)
⇒ The turn-on snubber ~~from~~ before acts like ZCS turn on (in limit)
but are not lossless or quasi-lossless.

⇒ Note: Varying degrees of "softness" exist, depending on the degree to which waveform rises are delayed, and waveform slopes near transitions (additional categorizations exist.)

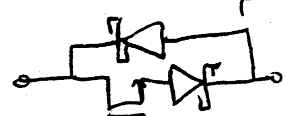
Notes on ZCS QR Buck (SEE HANDOUT / OVERHEAD)

Example #1: ZCS Quasi-Resonant Buck Converter

Explain operational Cycle

- Main switch turns on ZCS
- MAIN switch / Diode turns off ZCS
- Diode turns on ZCS
- Diode turns off ZCS

Alt sw/diode impl.



Explain: V_{out} control by f_{sw} control / Pulse density Modulation

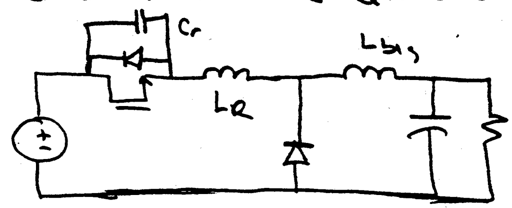
Explain: Exper. waveforms @ light, heavy load,

Adv: Smooth, soft waveform transitions
low switching losses to moderately high frequencies

Disadv: ZCS turn on loses junction cap energy
High conduction losses (compared to PWM) due to resonant action & energy sloshing about (→ half-wave version)
diode voltage rating 2x
requires frequency control over very wide range

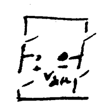
Other versions of this technique exist (Half-wave, ZVS versions) and for many converter types (boost, buck-boost, Cuk, sepic, etc.)

ex/ ZVS Half-wave QR buck converter



<u>Final aside</u>: This converter type is forced to use <u>frequency</u> control to achieve soft switching. (which has its disadvantages). We are very used to duty ratio (or fixed-frequency PWM) control, but there are actually many methods:

ex/ Fixed freq PWM
Frequency control
Phase-shift control → show full-bridge example to demo alternative methods
phase control (ac systems)
and more...



Next example: suppose we want to retain PWM control. We can do this (at a price)

<u>ZVS PWM Buck Converter Example</u>

Extra circuitry & control (+ increased device ratings) to allow soft-switched operation.

Explain operational cycle + duty ratio control approach

Main sw: ZVS turn on, ZVS turn off
Aux sw: ZVS/ZCS turn on, ZVS turn off
Diode: ZVS turn on, (poor) ZCS turn off

Advantages: Duty ratio control of main switch (over a range) (PWM)
low loss on main & aux switch @ turn on & off
junction cap on main sw is part of Cr (no turn-on loss)

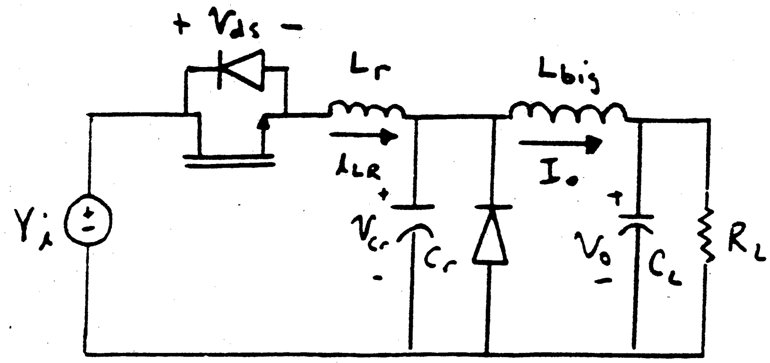
Disadvantages: Very high voltage rating on main switch (varies w/ load)
additional switch & control circuitry → complexity
only limited reduction of diode losses at turn off

Other versions of this approach exist (i.e. ZCS, other topologies)

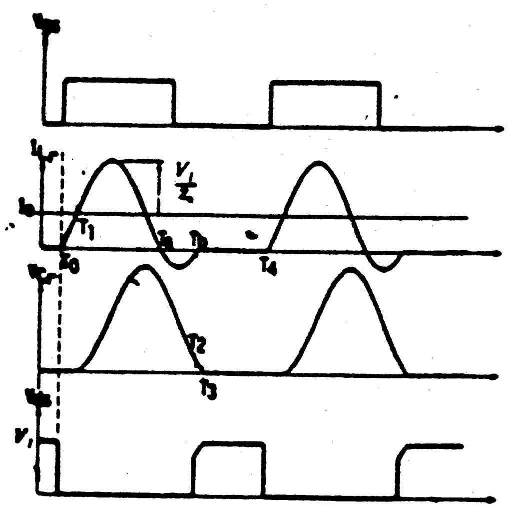
Many other soft-switching approaches exist, some with PWM Control (ex/ Zero-Voltage Transition Circuits), and some with other methods (ex/ phase-shift full bridge, resonant converters, etc.)

Next time: more soft switching techniques. We will focus on popular methods for bidirectional converters and inverters (esp 3Φ). Esp focus on RPI, ACCP, RDCL topologies.

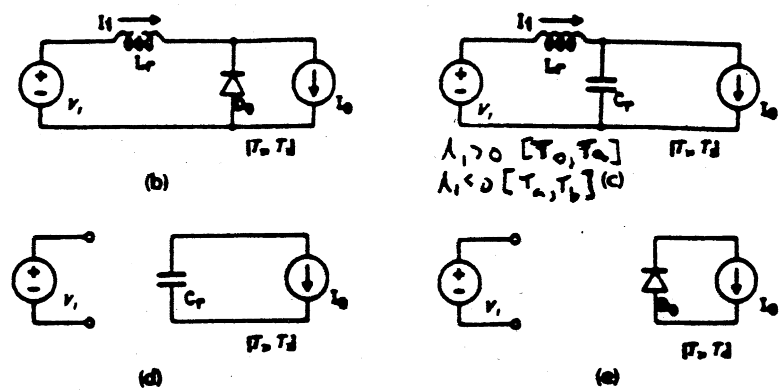
Full-Wave ZCS Quasi-Resonant Buck Converter



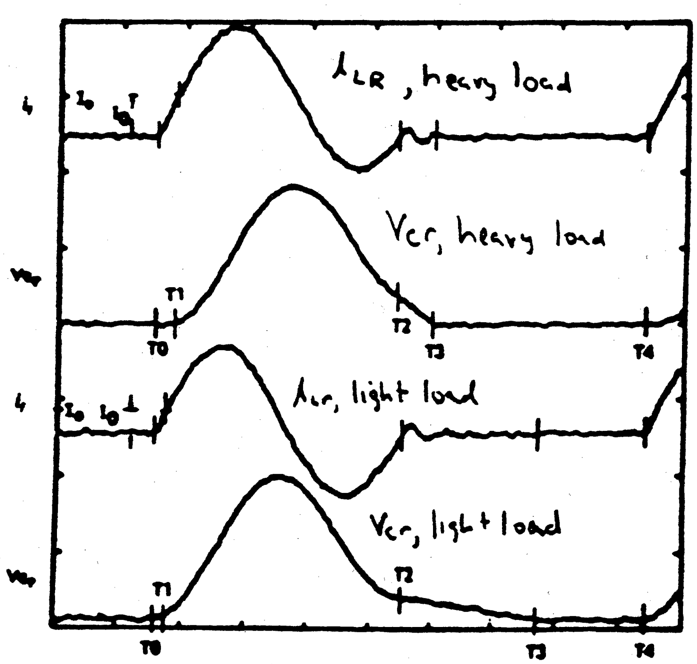
Converter



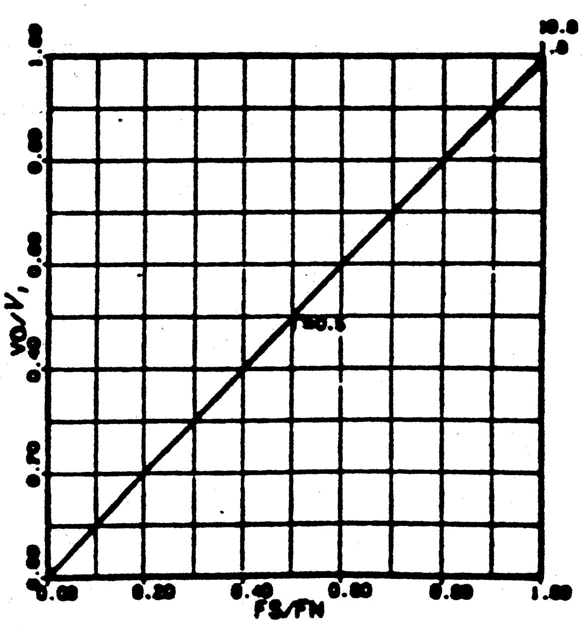
Ideal Waveforms



Operating Modes



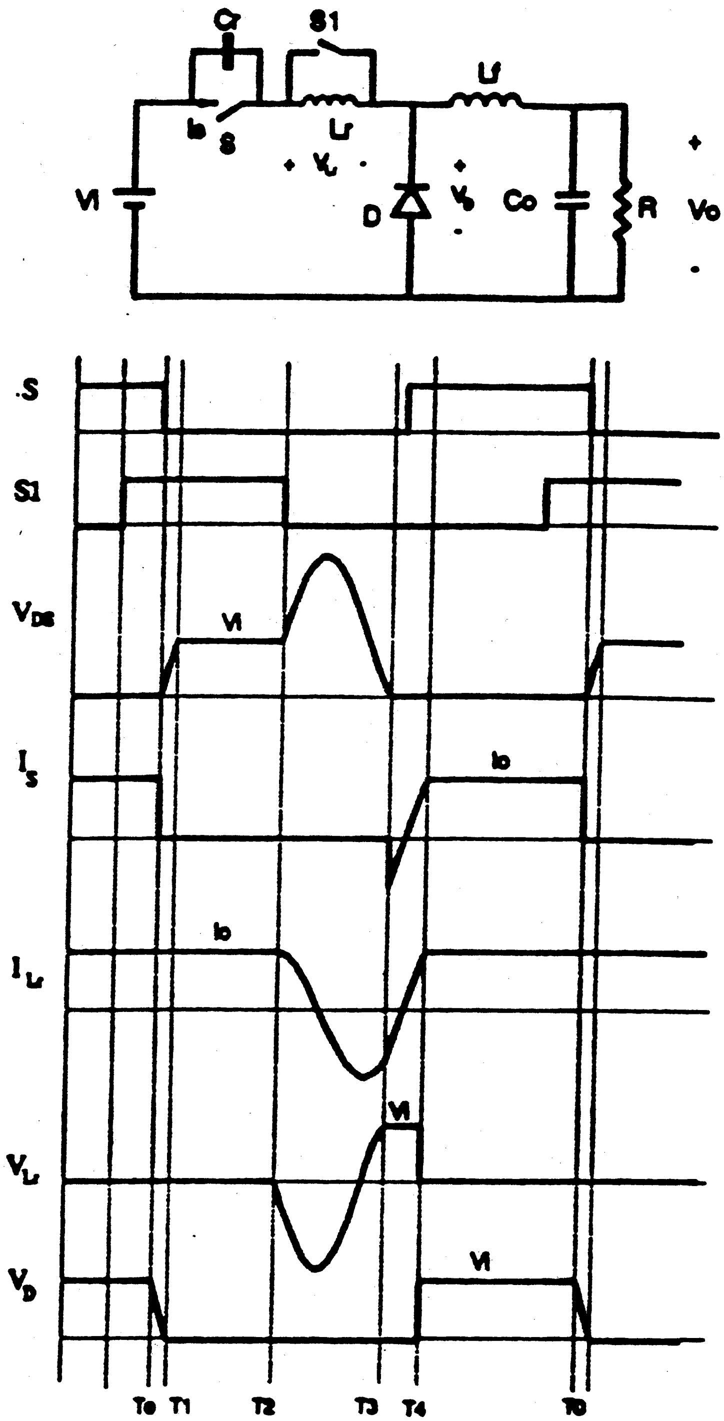
Waveforms at heavy, light loads



Control Characteristics

Figures from "High-Frequency Quasi-Resonant Converter Technologies" by F.C. Lee
Proc. IEEE, Vol. 76, No. 4, April 1988

ZVS PWM Buck Converter



Main Switch S:	ZVS Turn on, ZVS Turn off
Diode D:	ZVS Turn on, poor (high di/dt) ZCS turn off
Aux. Switch S1:	ZVS/ZCS Turn on, ZVS turn off

Figure from "An Overview of Soft-Switching Techniques for PWM Converters," by G. Hua and F.C. Lee European Power Electronics Journal, Vol. 3, No. 1, March 1993.