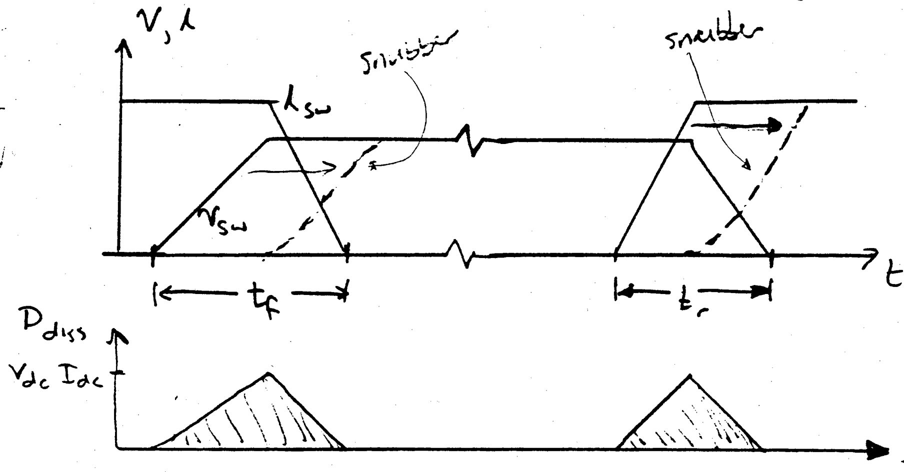
6.334 Power Electronics
Spring 2007

Power Electronics Notes - D. Perreault

★★ Soft-Switching Techniques

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

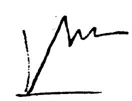


Turn off:
V rises 1st (diode on)
i falls 2nd

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

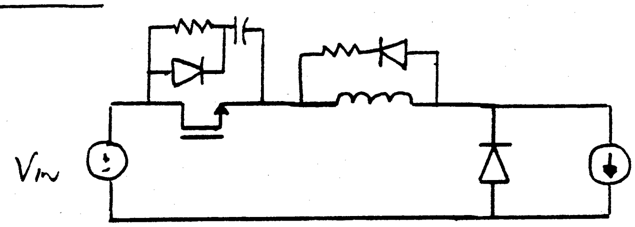
This has 3 deleterious effects:

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.



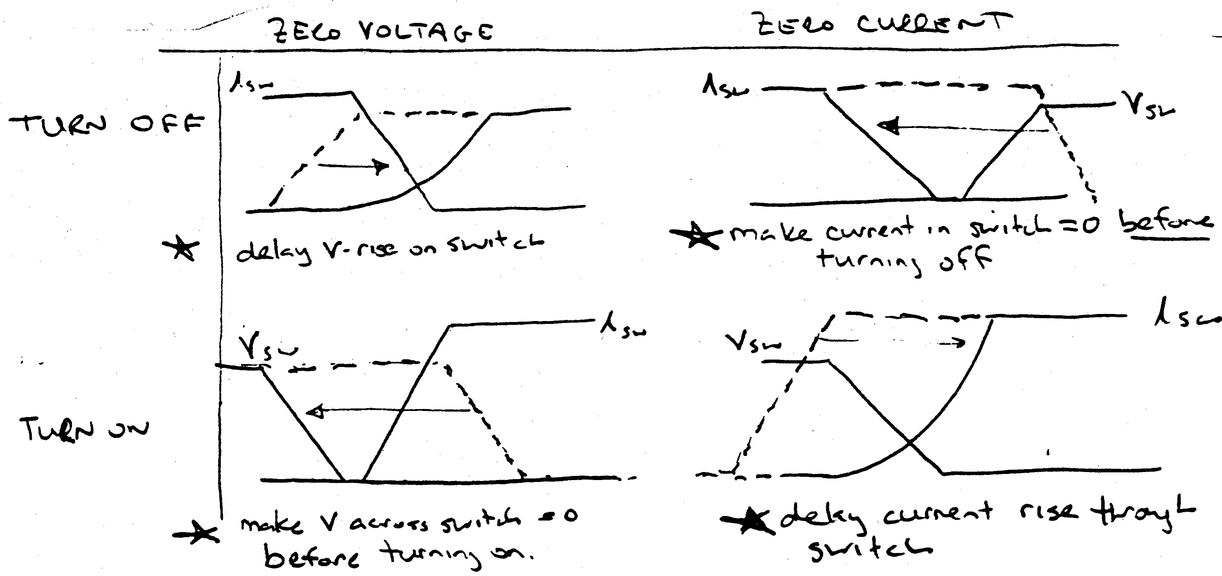
Today: Soft-Switching techniques try to mitigate these effects without adding substantial losses.

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...

Power Electronics Notes - D. Perreault



⇒ 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.

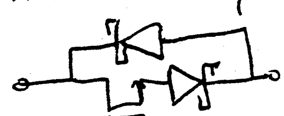
⇒ Note: Varying degrees of "softness" exist, depending on the degree to which waveform rises are delayed, and waveform slopes near transitions (additional categorizations exist.)

Notes on ZCS QR Buck (SEE HANDOUT / OVERHEAD)

Example #1: ZCS Quasi-Resonant Buck Converter

Explain operational Cycle

Alt sw/Diode impl.



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

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

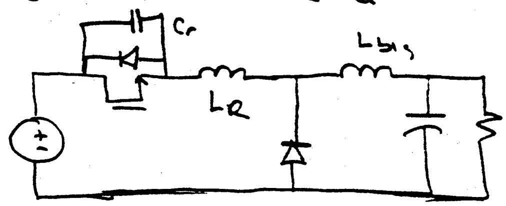
Explain: Exper. waveforms @ light, heavy load.

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

Power Electronics Notes - D. Perreault

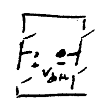
ex/ ZVS Half-wave QR buck converter



FINAL ASIDE: This converter type is forced to use frequency 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
phase control (ac systems)
and more...

→ show full-bridge example to demo alternative methods



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

ZVS PWM Buck Converter Example

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

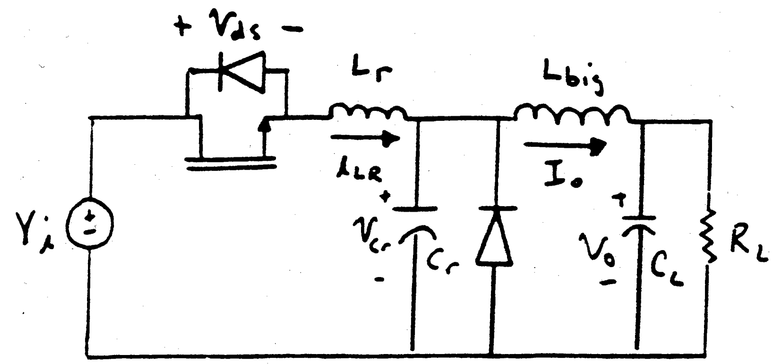
Explain operational cycle + duty ratio control approach

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

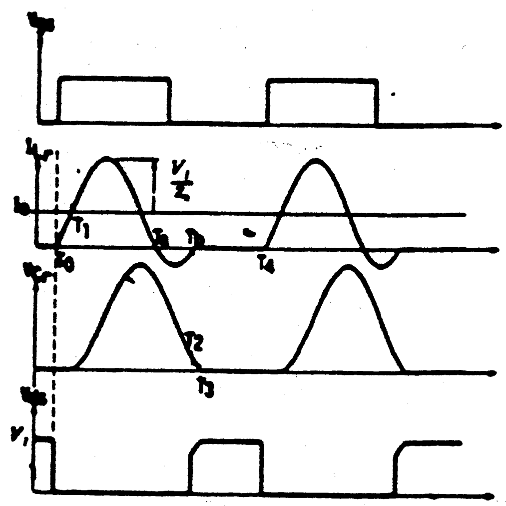
Advantages: Duty ratio control of main switch (over a range) (PWM)
low loss on main & aux switch @ turn on & off
junction cap on main sw is part of Cr (no turn-on loss)

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

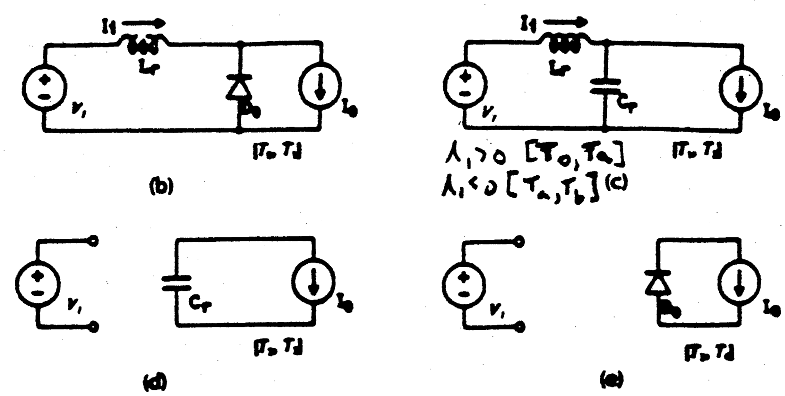
Full-Wave ZCS Quasi-Resonant Buck Converter



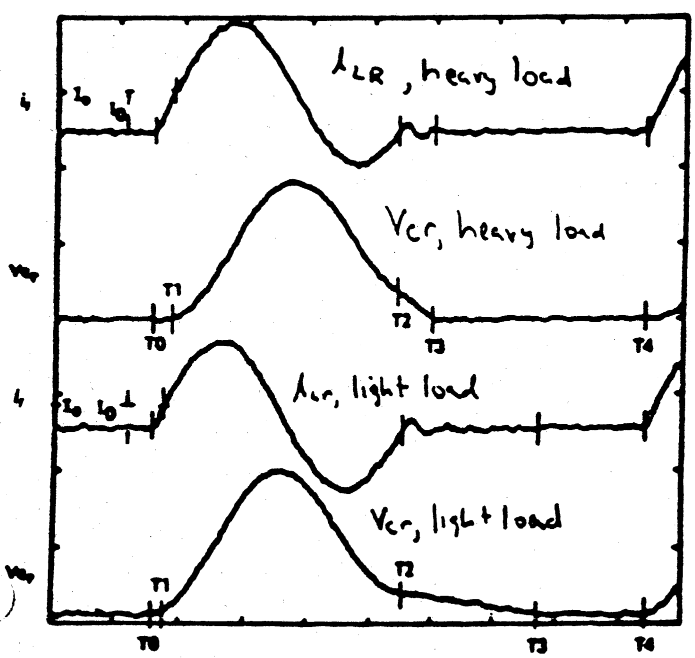
Converter



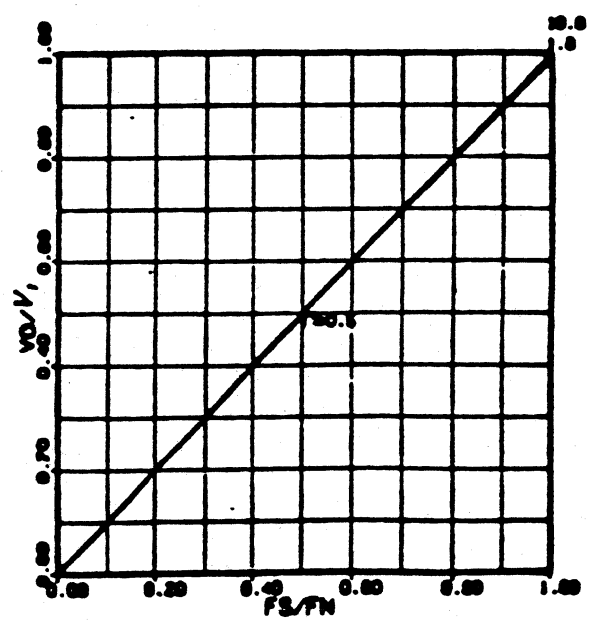
Ideal Waveforms



Operating Modes



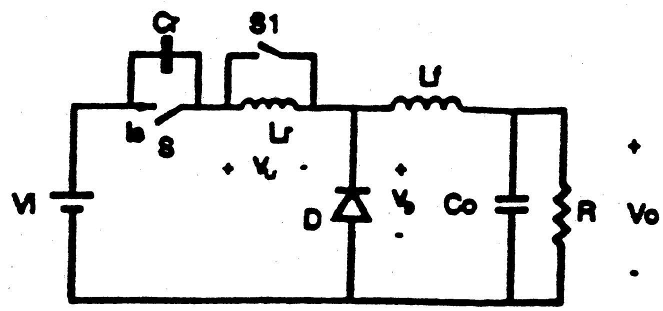
Waveforms at heavy, light loads

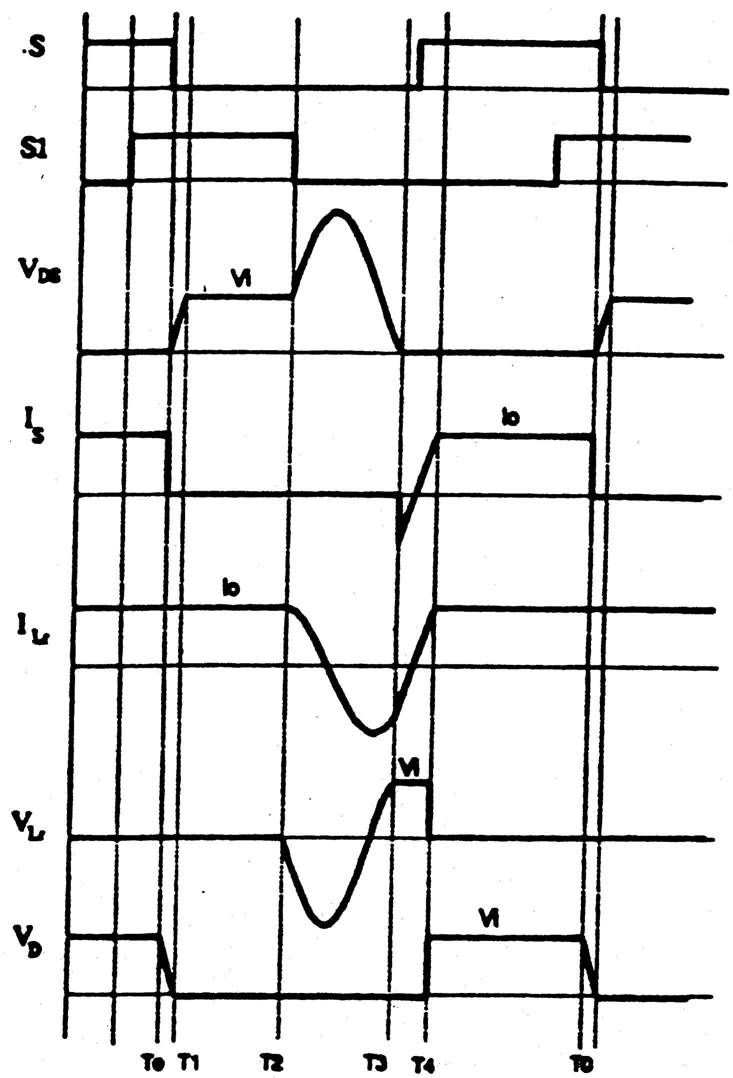


Control Characteristics

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

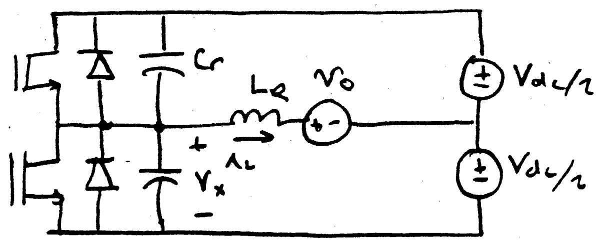
Figure from "An Overview of Soft-Switching Techniques for PWM Converters," by G. Hua and F.C. Lee European Power Electronics Journal, Vol. 3, No. 1, March 1993.

Power Electronics Notes - D. Perreault

RESONANT POLE INVERTER

ZERO VOLTAGE TURN ON AND TURN OFF OF DEVICES

⇒ First, consider switching cycle (overhead / handout)



⇒ overall operation: $\langle i_L \rangle \approx \dfrac{i_{p+} + i_{p-}}{2}$

control i_{p+}, i_{p-} to achieve desired $\langle i_L \rangle$ in a switching cycle.

also, there are requirements on i_{p+}, i_{p-} to achieve soft sw.

i_{p+} must be pos. enough to ring V_x from V_{dc} to 0.

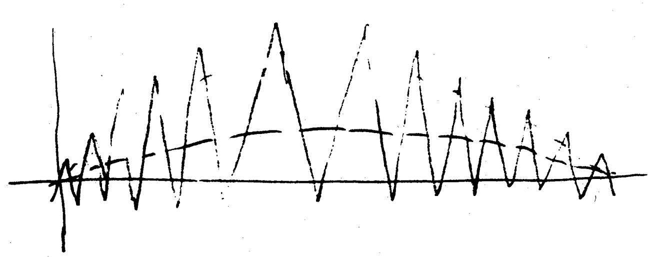
i_{p-} must be neg. enough to ring V_x from 0 to V_{dc}.

⇒ derived conditions: define $i_{min} = 2\sqrt{\dfrac{C_r V_{dc} |V_{cf}|}{L_r}}$

If $V_o > 0$ $\quad |i_{p+}| > i_{min}$, $|i_{p-}| > 0$

$V_o < 0$ $\quad |i_{p+}| > 0$, $|i_{p-}| > i_{min}$

Pick i_{p+}, i_{p-} to satisfy these constraints and to yield desired $\langle i_L \rangle$



$$f_{sw} = \frac{\frac{1}{4}V_{dc}^2 - V_{cf}^2}{V_{dc} L_r (i_{p+} + i_{p-})} \sim \frac{1}{\langle i_L \rangle}$$

so to control $\langle i_L \rangle$ we get widely varying switching freq.

So: RPI gives us : ZVS soft switching
small resonant components
simple control

But : Requires Variable f control
yields high output current ripple

Another approach which eliminates these requirements at the expense of high complexity:

Auxiliary Resonant Commutated Pole Inverter (ARCP)

→ uses additional switches & res components (aux circuit) to allow the switch state to be changed whenever desired

→ many operational modes, depending on state.

⇒ go through example commutation sequence (if time)

ARCP gives us : Total control of bridge leg at ZVS
(aux circuit is ZCS)

BUT : Very high control & sensing complexity.

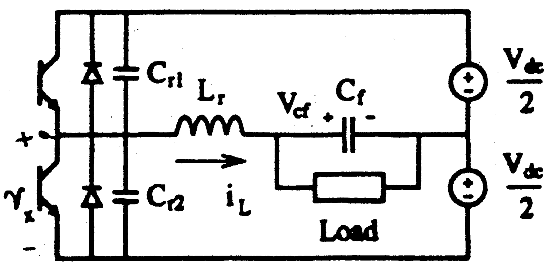
→ suitable for very high power converters

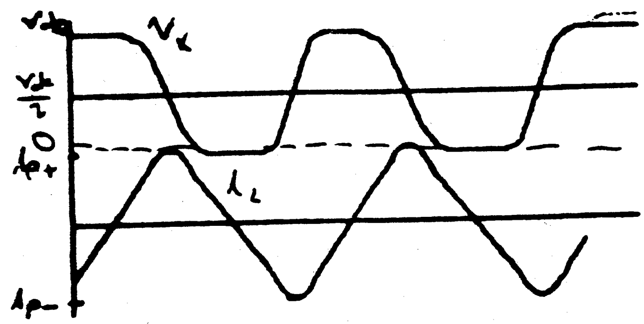
Final notes: Many issues w/ soft switching we have ignored.

→ device physics & switching characteristics
(not all devices operate well w/ ZVS, ZCS)

→ control complexity, implementation
(dead times, etc.)

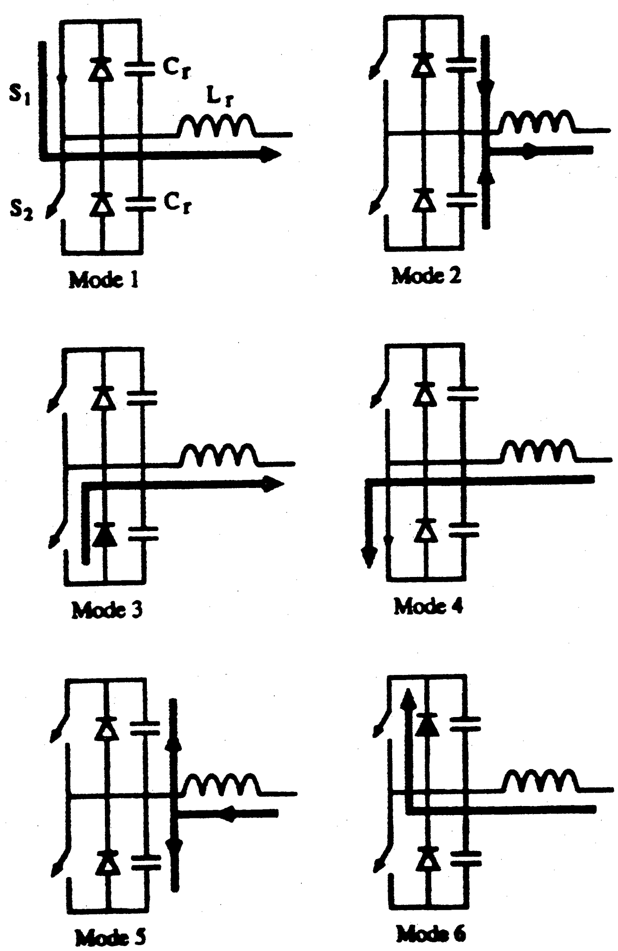
Resonant Pole Inverter Operation





(a) The half-bridge Resonant Pole Inverter

(b) RPI output current waveform



An operational cycle of the Resonant Pole Inverter

Figures from "Analysis and Control of a Cellular Converter System with Stochastic Ripple Cancellation and Minimal Magnetics", by D. Perreault and J. Kassakian, IEEE Trans. Power Elect., Vol. 12, No. 1, Jan. 1997.

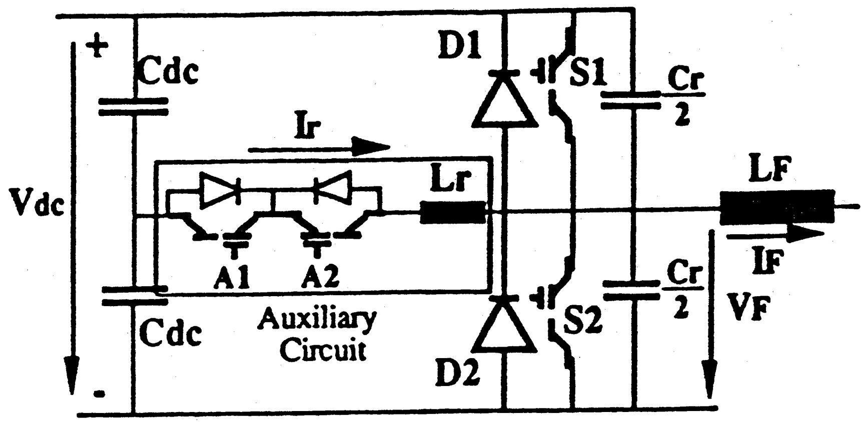


Fig. 12a. The Auxiliary Resonant Commutated Pole (ARCP).

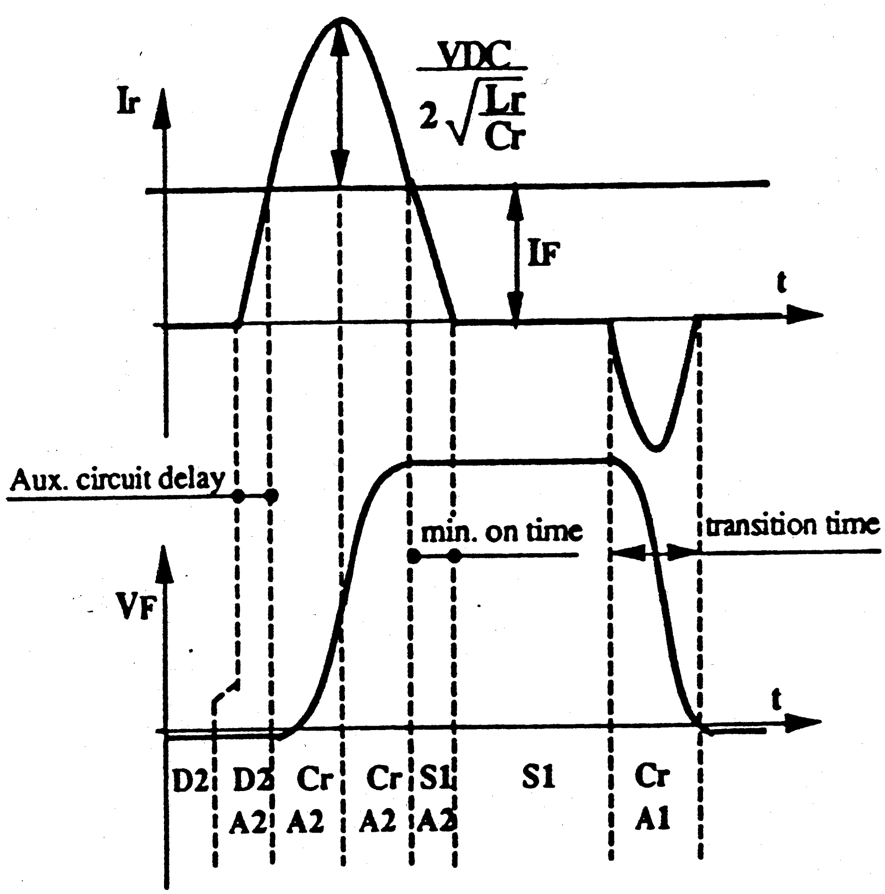


Fig. 12b. Basic switching sequence of ARCP phase leg.

Figures from PESC '91 Tutorial

R.W. De Doncker, GE-CRD, Resonant Pole Converter, PESC-91, Boston, MA.

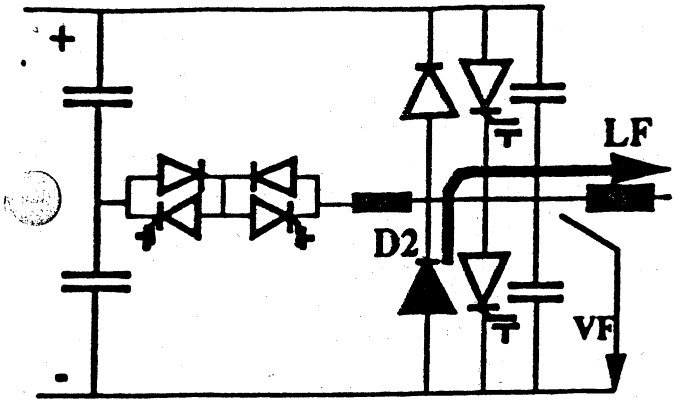


Fig. 13a. ARCP commutation from Diode

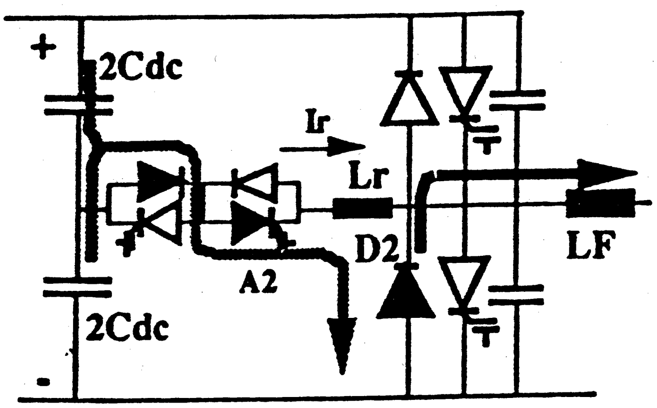


Fig. 13b. ARCP commutation from Diode

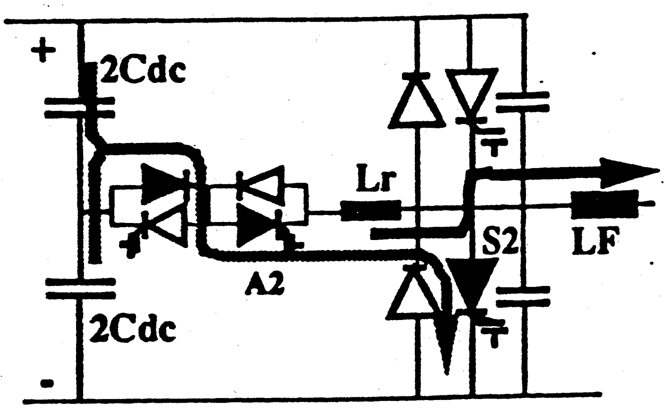


Fig. 13c. ARCP commutation from Diode

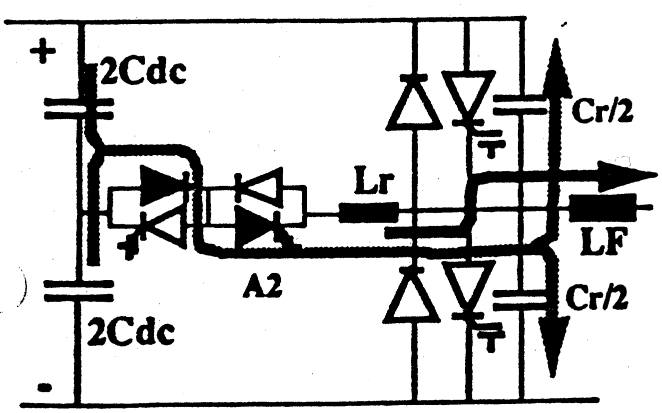


Fig. 13d. ARCP commutation from Diode

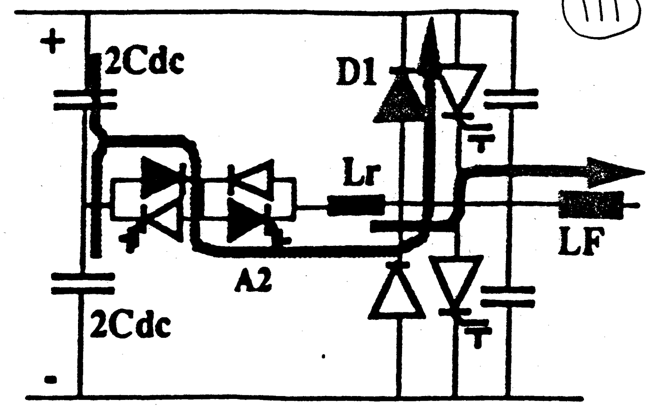


Fig. 13e. ARCP commutation from Diode

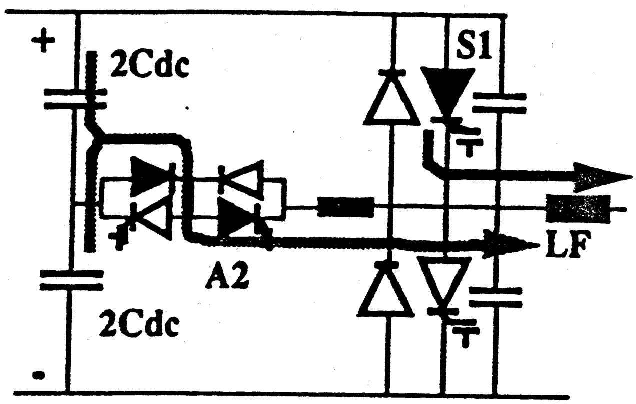


Fig. 13f. ARCP commutation from Diode

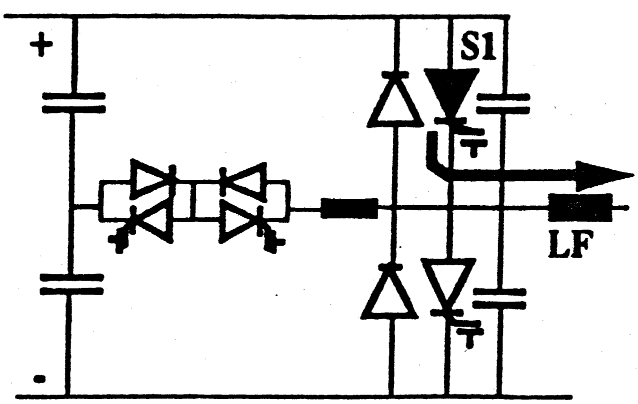


Fig. 13g. ARCP commutation from Diode

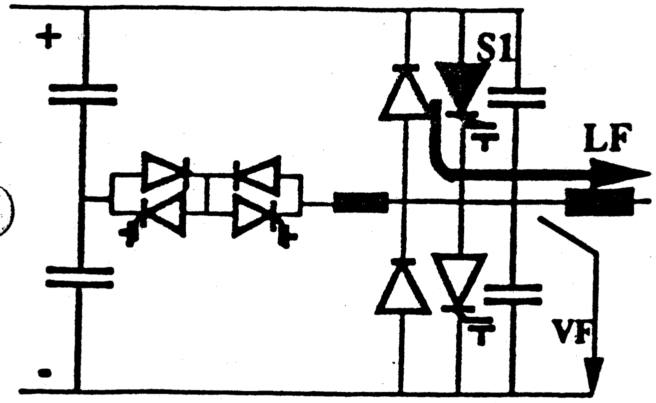


Fig. 14a. ARCP commutation from Switch - Low Current.

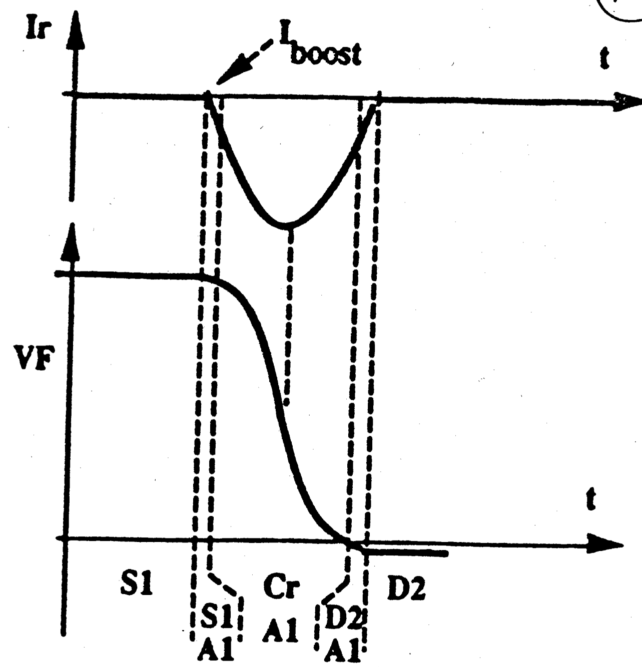
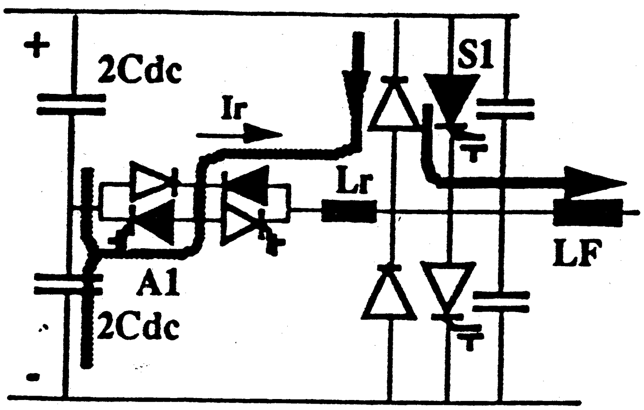
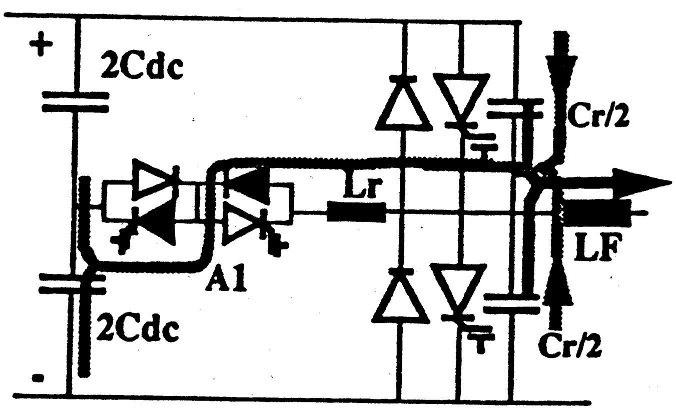


Fig. 14. ARCP commutation from Switch - Low Current.



4b. ARCP commutation from Switch - Low Current.



ig. 14c. ARCP commutation from Switch - Low Current.

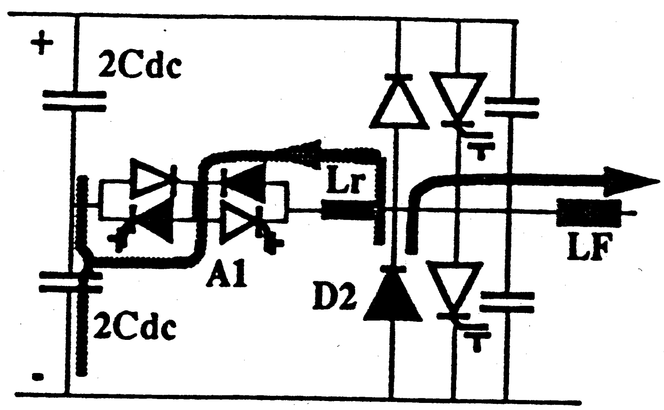


Fig. 14d. ARCP commutation from Switch - Low Current.