EE-464 STATIC POWER CONVERSION-II

Resonant Converters

Ozan Keysan

keysan.me

Office: C-113 • Tel: 210 7586

Advantages of High Switching Frequency?

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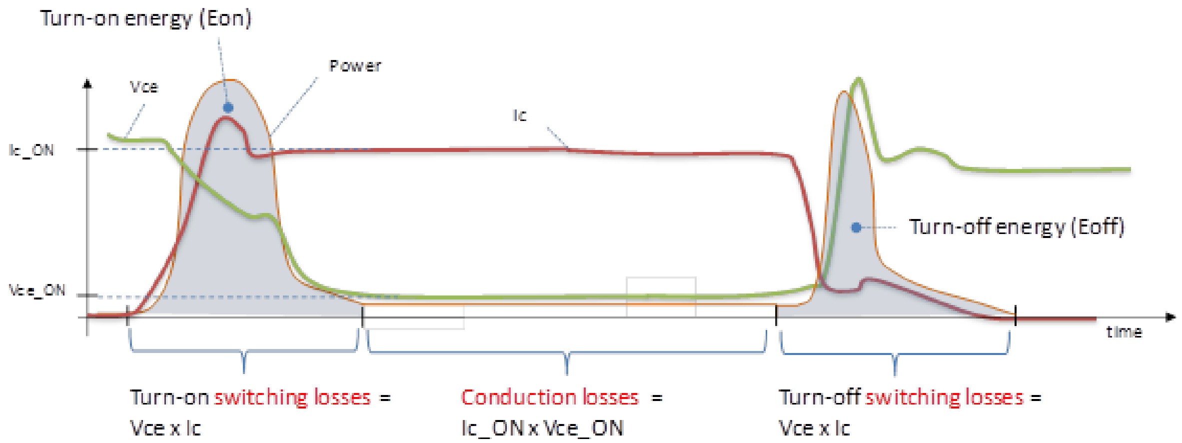
Disadvantages of High Switching Frequency?

- Increased switching losses

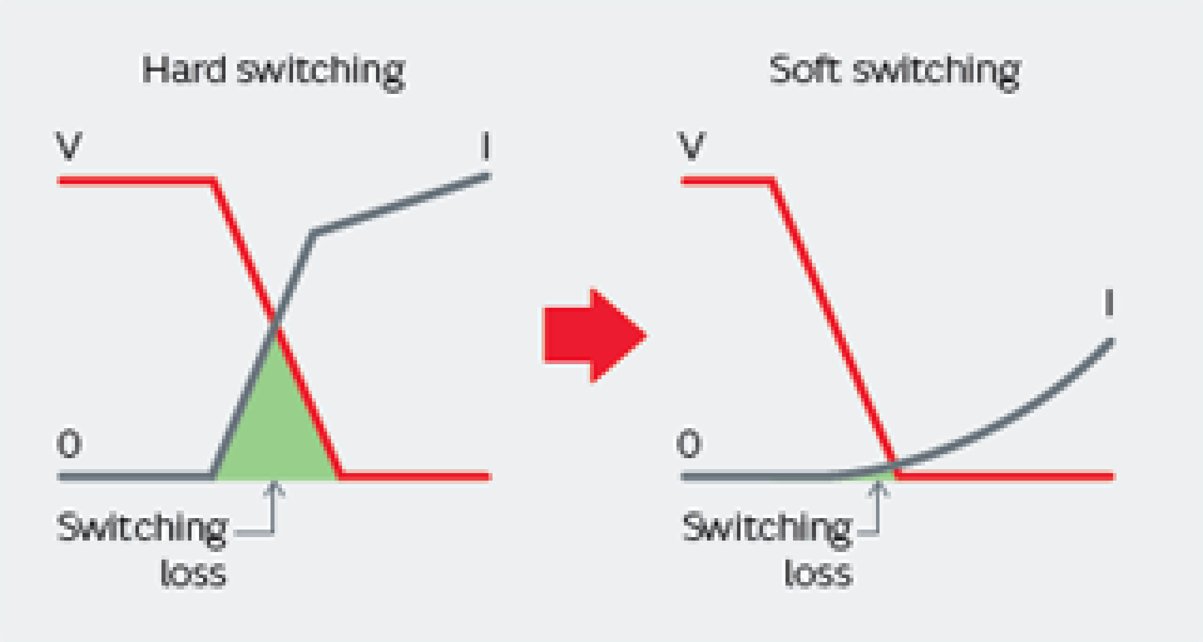
Switching Loss



You have more turn-on, turn-off energy dissipation as the frequency increases

Hard Switching vs. Soft Switching

Hard Switching vs. Soft Switching



Hard Switching vs. Soft Switching

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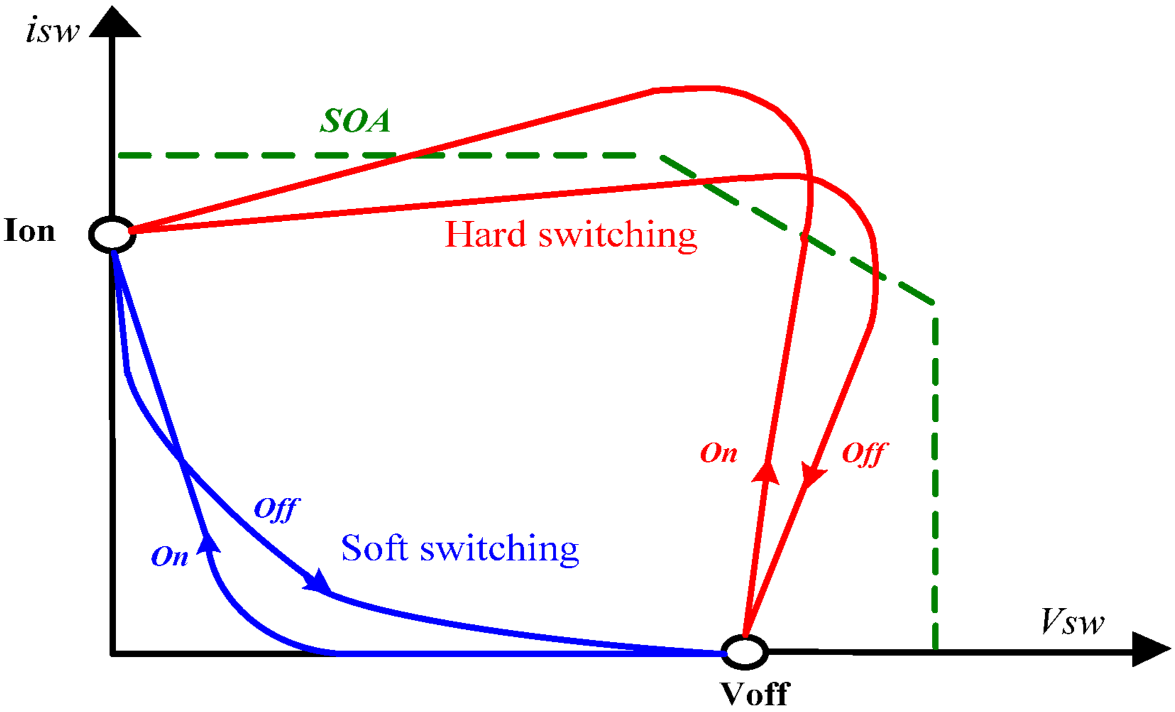

Resonant Converters

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Two main types of switching:

Resonant Converters

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- when voltage is zero (ZVS)

Resonant Converters

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- when voltage is zero (ZVS)
- when current is zero (ZCS)

Resonant Converters

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There are many resonant converter topologies.

Most common types:

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Most common types:

- Resonant Switch Converters
- Load Resonant Converter
- Resonant DC-link Converter

Review: RLC Resonant Circuits

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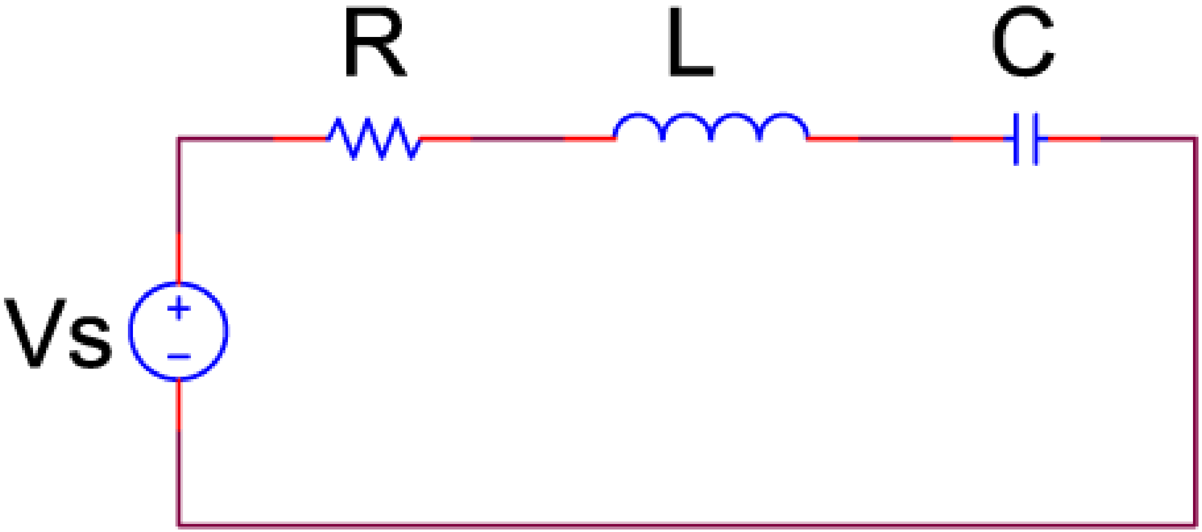
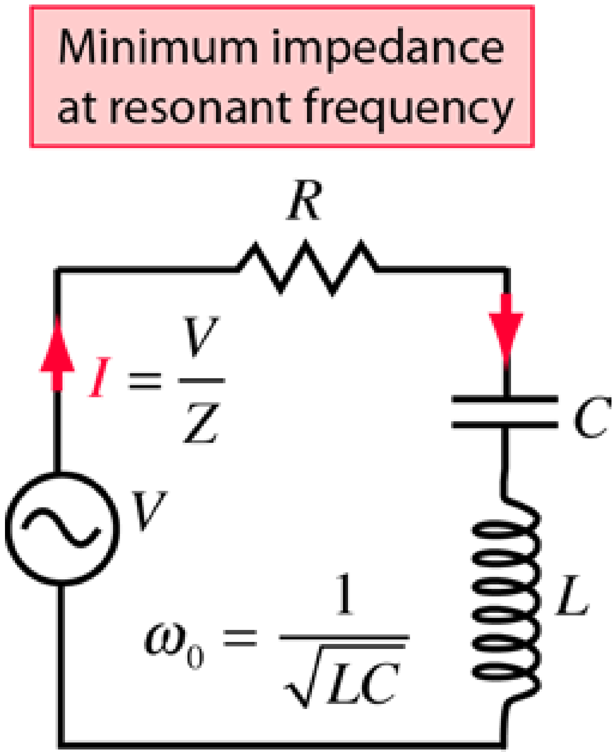


Review: RLC Resonant Circuits



Review: RLC Resonant Circuits

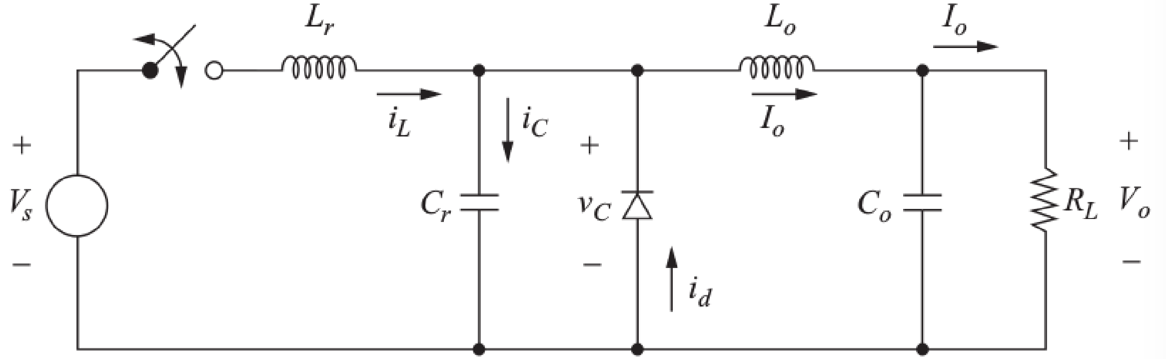
- Series RLC Circuit Animation
- Series RLC Circuit Animation
- Signal Transmission and Reflection

Resonant Switch Converter: Zero Current Switching

W. Hart., Power Electronics, Ch.9

Resonant Switch Converter: Zero Current Switching

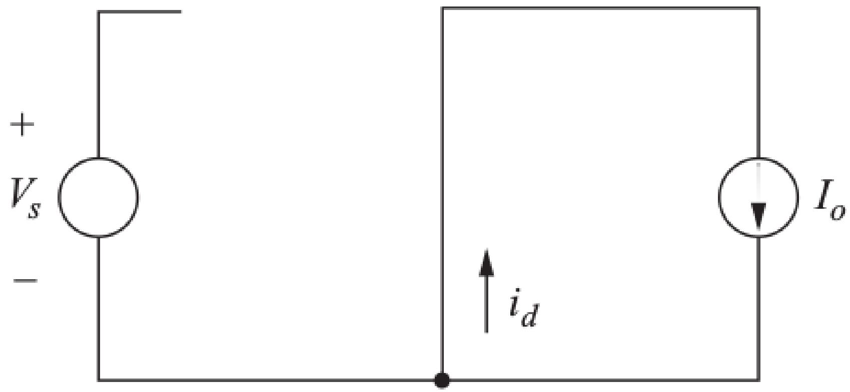
W. Hart., Power Electronics, Ch.9



Assumption: L_o **is large enough,** I_o **is constant**

Operating Mode: $t < 0$

Operating Mode: $t < 0$



Switch open, Diode ON (frewheeling), $v_C = 0$

Operating Mode: $0 < t < t_1$

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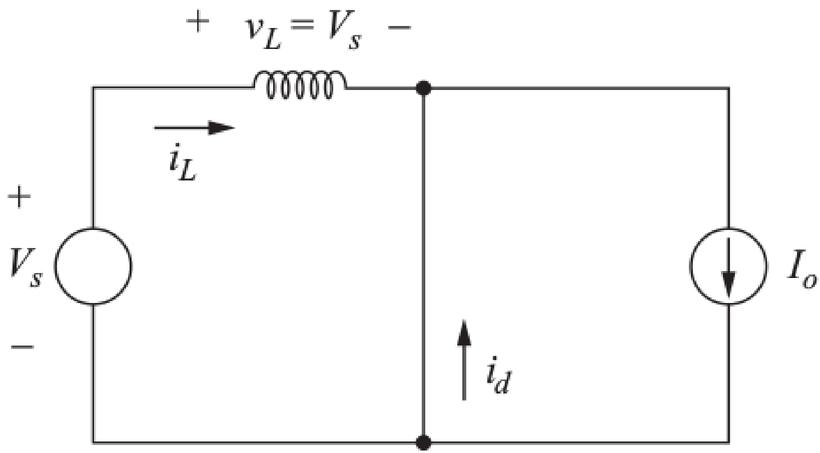
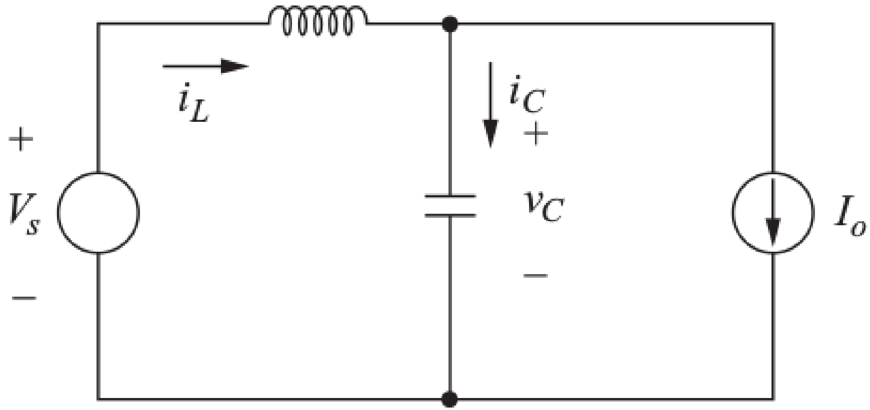


Switch closed, L_r start charging

$i_L < I_o$ so the diode is still ON

Operating Mode: $t_1 < t < t_2$

Operating Mode: $t_1 < t < t_2$



When $i_L = I_o$, the diode turns OFF

Excess inductor current charges the capacitor $v_C > 0$

Operating Mode: $t_1 < t < t_2$

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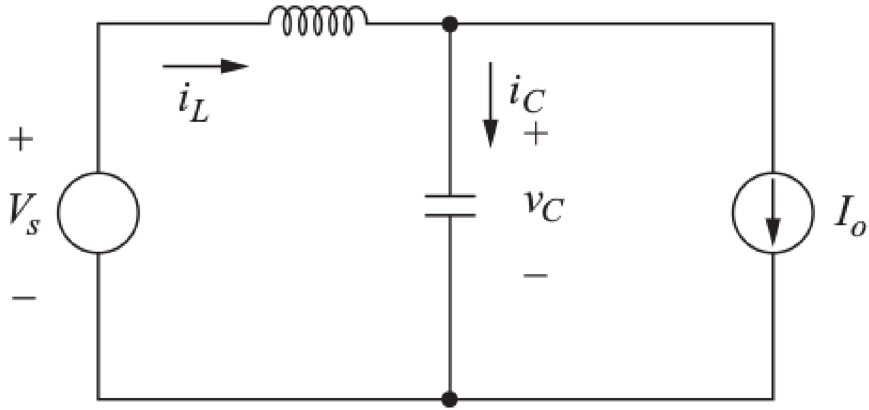

If no action is taken, oscillation starts in the LC circuit!

Operating Mode: $t_2 < t < t_3$

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Turn the switch off, when $i_L = 0$

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=Zero current switching!

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Alternatively a unidirectional switch (SCR) can be used.

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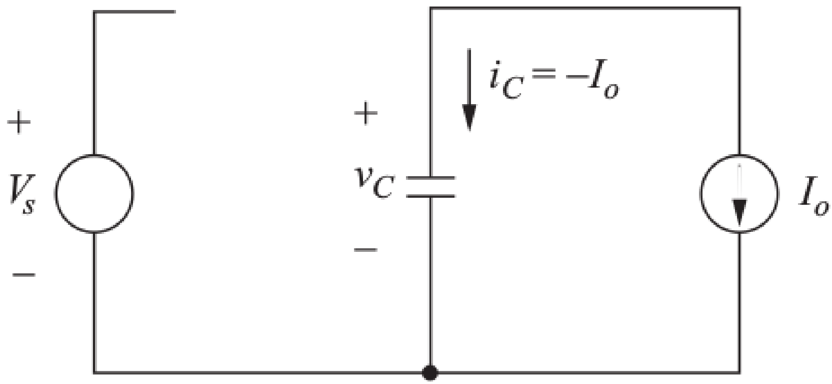
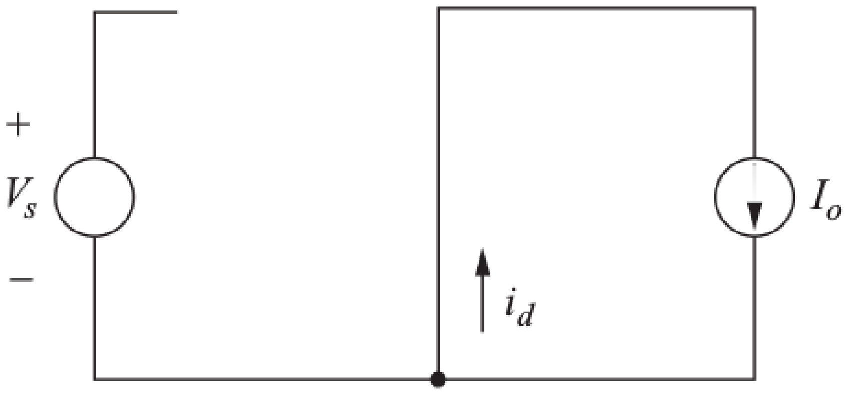


Very small switching loss (due to capacitances in the switch)

Output current is supplied by C (discharges linearly)

Initial Mode: $t_3 < t < T$

Initial Mode: $t_3 < t < T$

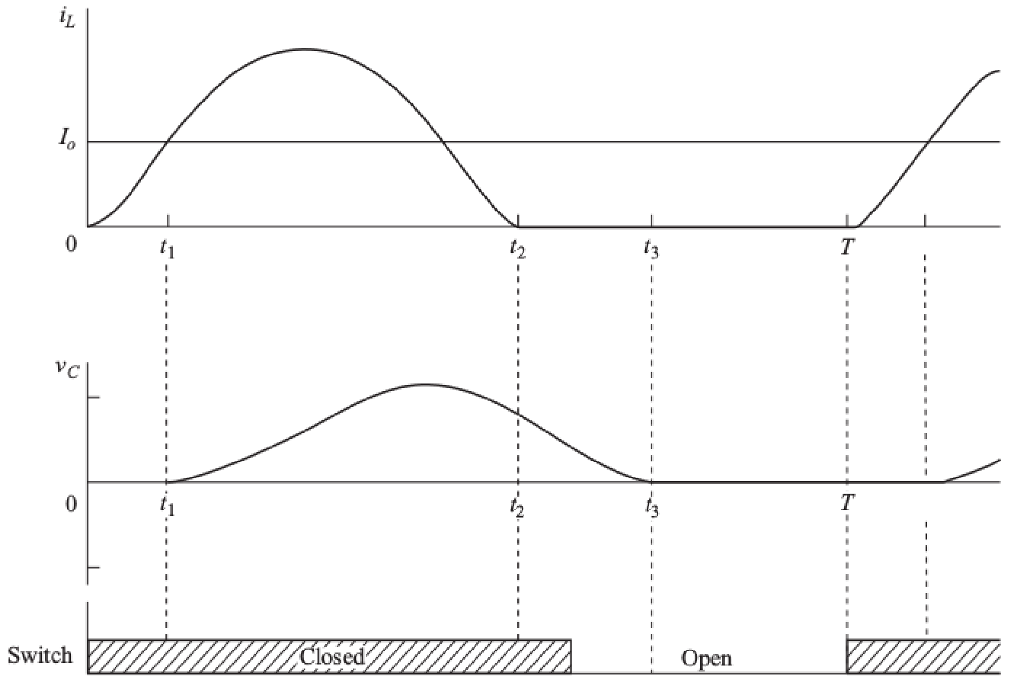


$v_C = 0$, diode starts freewheeling,

Switch ready to to turn ON (zero current)

Analysis of the Operating Modes

W. Hart., Power Electronics, Ch.9-2



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The moment that the current reaches to Io is:

$$t_1 = \frac{I_o L_r}{V_s}$$

Operating Mode: $t_1 < t < t_2$

Diode is off, capacitor voltage starts building up:

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Diode is off, capacitor voltage starts building up:

$$v_c(t) = V_s - L_r \frac{di_L(t)}{dt}$$

Operating Mode: $t_1 < t < t_2$

Differentiating and solving second order LC circuit (as in Ch9.2)

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Differentiating and solving second order LC circuit (as in Ch9.2)

$$i_L(t) = I_o + \frac{V_s}{Z_o} sin\omega_0(t - t_1)$$

$$Z_0 = \sqrt{\frac{L_r}{C_r}}$$

$$\omega_0 = \frac{1}{\sqrt{L_r C_r}}$$

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$$\omega_0 = \frac{1}{\sqrt{L_r C_r}}$$

$$t_2 - t_1 = \frac{1}{\omega_0}[sin^{-1}(\frac{-I_0 Z_0}{V_s})]$$

Operating Mode: $t_1 < t < t_2$

Capacitor voltage can be expressed as:

$$V_c(t) = V_s[1 - cos(\omega_0(t - t_1))]$$

which implies capacitor voltage can reach up to 2 Vs (a disadvantage of resonant converters)

Operating Mode: $t_2 < t < t_3$

As the inductor current reaches to zero at t2, the switch can be openced with no current (ZCS)

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Capacitor discharges with constant load current.

$$V_c(t) = \frac{I_0}{C_r}(t_2 - t) + V_c(t_2)$$

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Capacitor discharges with constant load current.

$$V_c(t) = \frac{I_0}{C_r}(t_2 - t) + V_c(t_2)$$

If Vc=0 at t3:

$$t_3 - t_2 = \frac{C_r v_c(t_2)}{I_o} = \frac{C_r V_s[1 - cos(\omega_o(t_2 - t_1))]}{I_o}$$

Operating Mode: $t_3 < t < T$

In this interval switch is off (diode freewheeling)

The length of this invertal directly controls the output voltage.

The switching frequency should be adjusted so that t3 is less than period (T).

Derivation of the Output Voltage

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Use energy balance (L-C are lossless)

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$$V_o = V_s f_s [\frac{t_1}{2} + (t_2 - t_1) + (t_3 - t_2)]$$

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Use energy balance (L-C are lossless)

$$V_o = V_s f_s [\frac{t_1}{2} + (t_2 - t_1) + (t_3 - t_2)]$$

$V_o < V_s$ operates as a buck converter

Output voltage is controlled by the switching frequency!

Analysis of the Operating Modes

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Time internals are a function of output current

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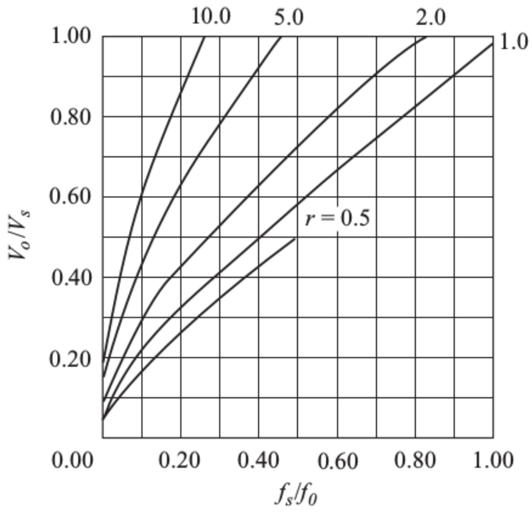
Time internals are a function of output current

Load changes switching frequency must be changed



Example (Hart 9-1)

Resonant Switch Converter: Zero Voltage Switching

W. Hart., Power Electronics, Ch.9

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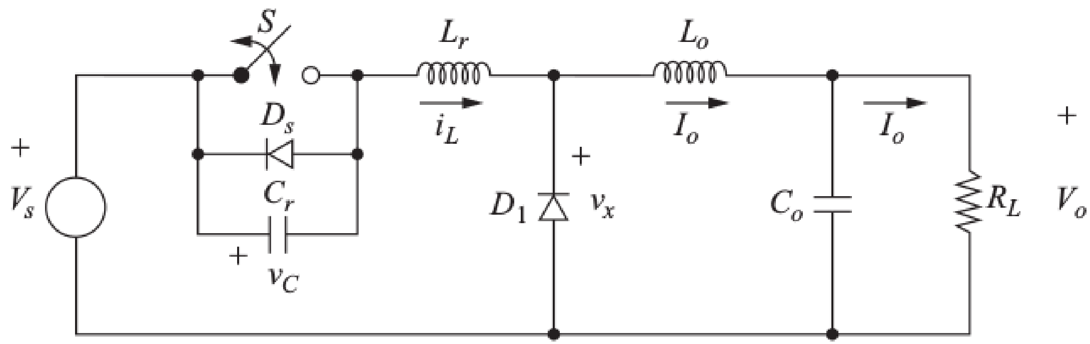
W. Hart., Power Electronics, Ch.9



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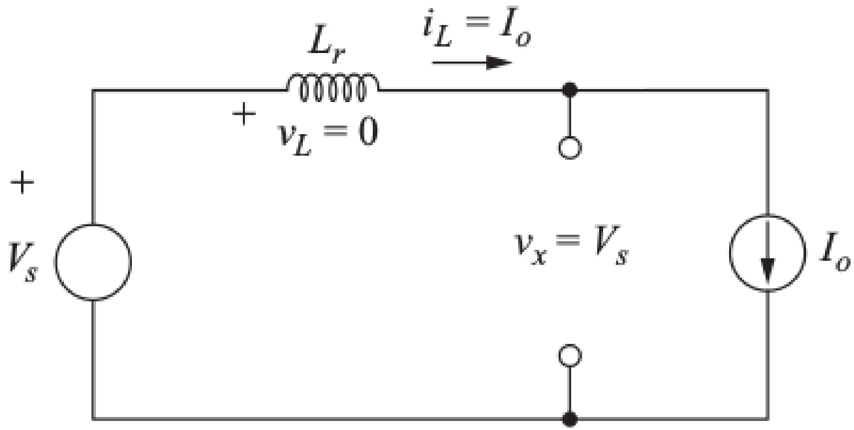

D1 off, switch ON, $i_L = I_o$

Operating Mode: $0 < t < t_1$

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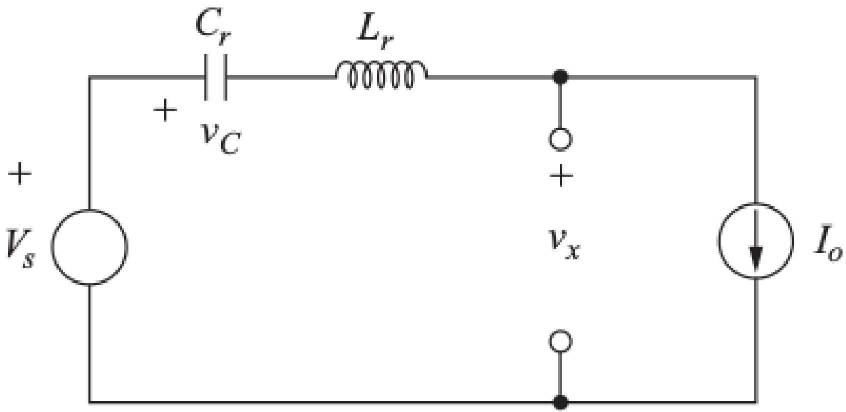
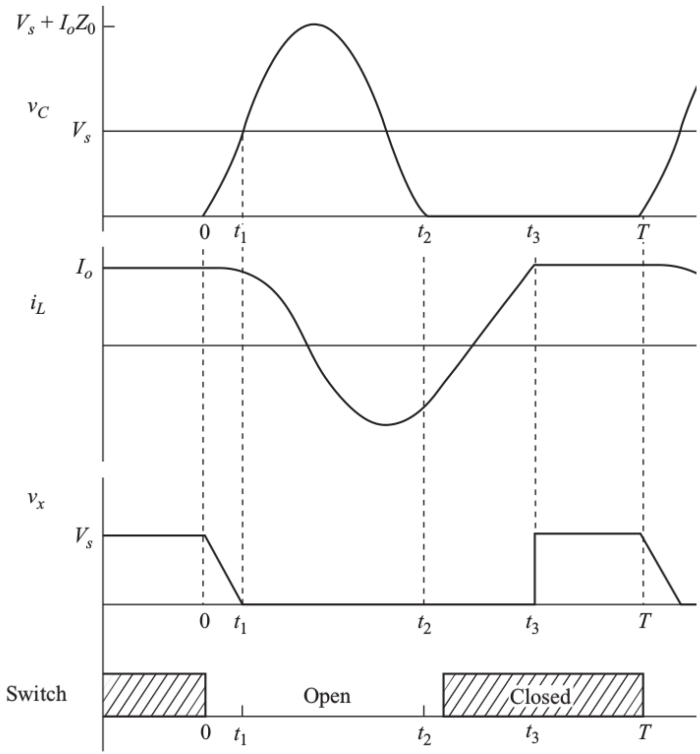


Switch opened, v_C start charging linearly

Resonant Switch Converter: Zero Voltage Switching



Operating Mode: $t_1 < t < t_2$

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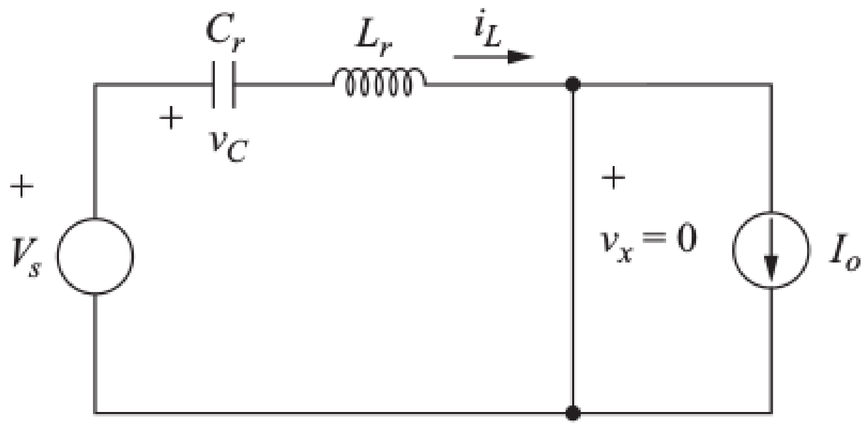
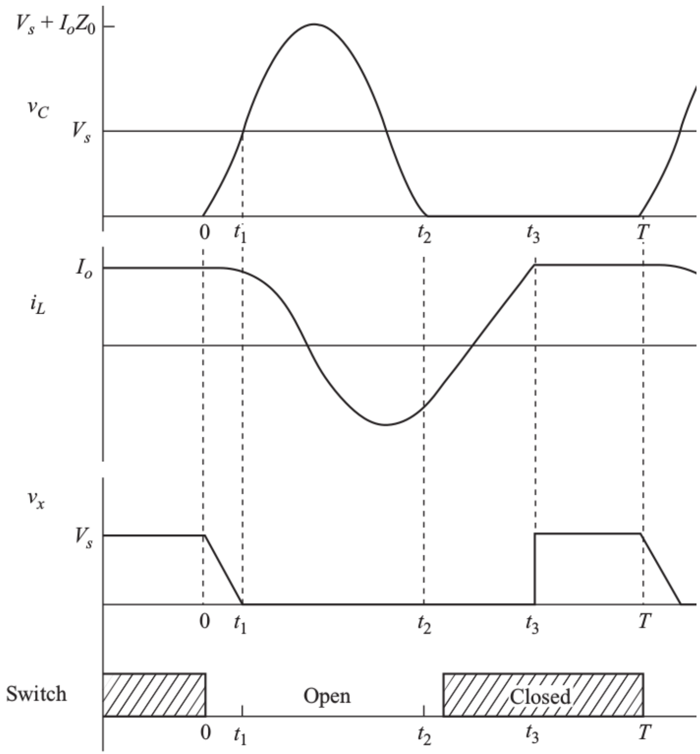


When $v_C = V_s$, the diode (D1) is forward biased

LC resonant circuit start oscillating,

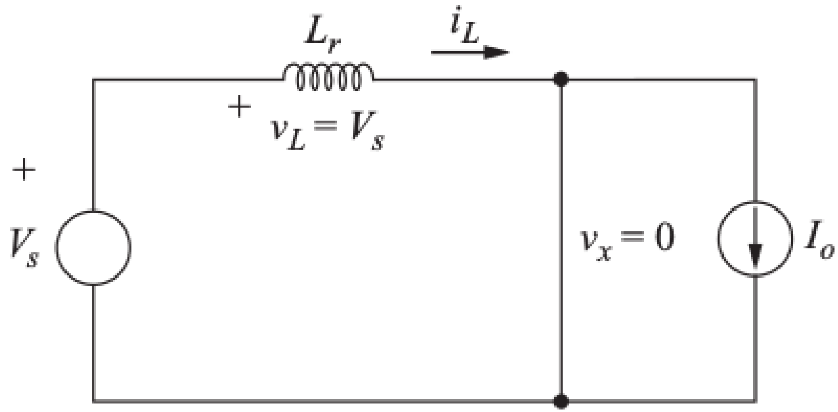
When $v_C = 0$, the diode (Ds) turns on to carry iL. (which is negative)

Resonant Switch Converter: Zero Voltage Switching



Operating Mode: $t_2 < t < t_3$

Operating Mode: $t_2 < t < t_3$



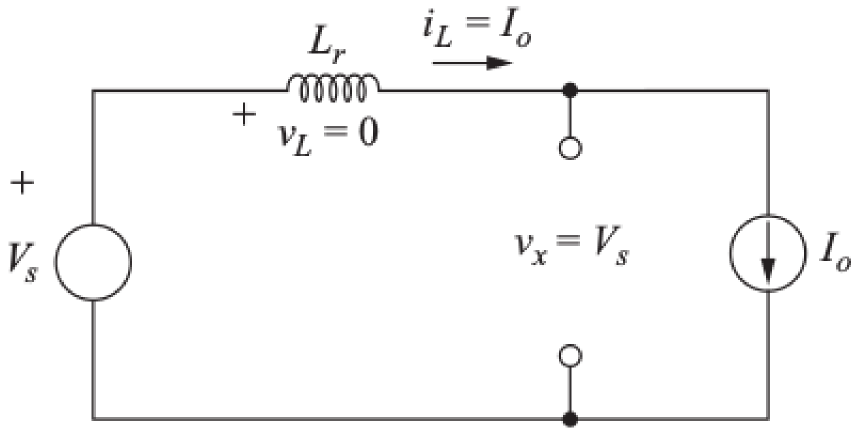
Ds is ON, $V_L = V_s$, inductor current increases linearly

Switch should be closed just after Ds turns on (zero voltage switching)

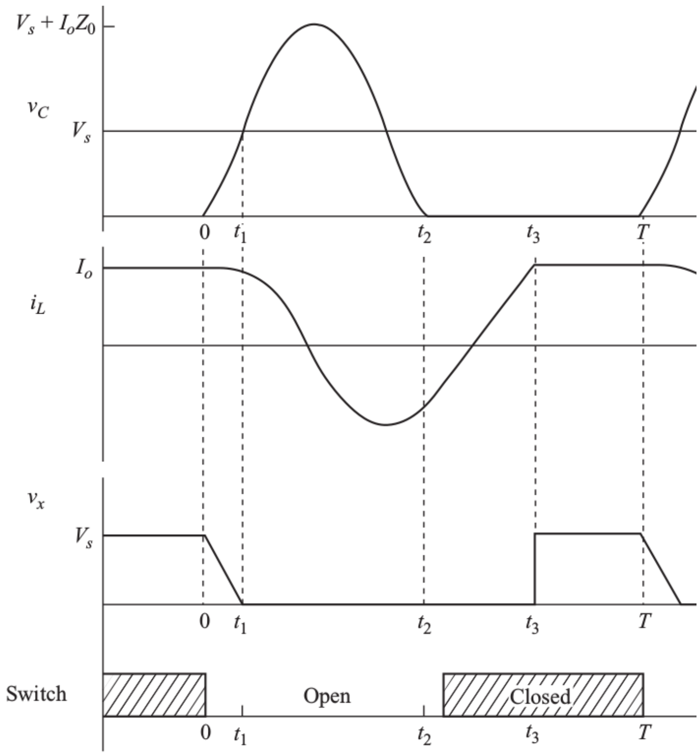
When $i_L = I_o$, D1 is off, and back to the initial position

Initial Mode: $t_3 < t < T$

Initial Mode: $t_3 < t < T$



Resonant Switch Converter: Zero Voltage Switching



Resonant Switch Converter: Zero Voltage Switching

Output voltage=?

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Output voltage = Average of $v_x(t)$

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Resonant Switch Converter: Zero Voltage Switching

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$v_x(t) = 0$ for $t_1 < t < t_3$

$v_x(t) = V_s$ for $t_3 < t < T$

Calculate the average voltage

Resonant Switch Converter: Zero Voltage Switching

Output voltage

Resonant Switch Converter: Zero Voltage Switching

Output voltage

$$V_o = \frac{V_s}{T}[\frac{t_1}{2} + (T - t_3)]$$

Resonant Switch Converter: Zero Voltage Switching

Output voltage

$$V_o = \frac{V_s}{T}[\frac{t_1}{2} + (T - t_3)]$$

or

$$V_o = V_s[1 - f_s(t_3 - \frac{t_1}{2})]$$

Resonant Switch Converter: Zero Voltage Switching

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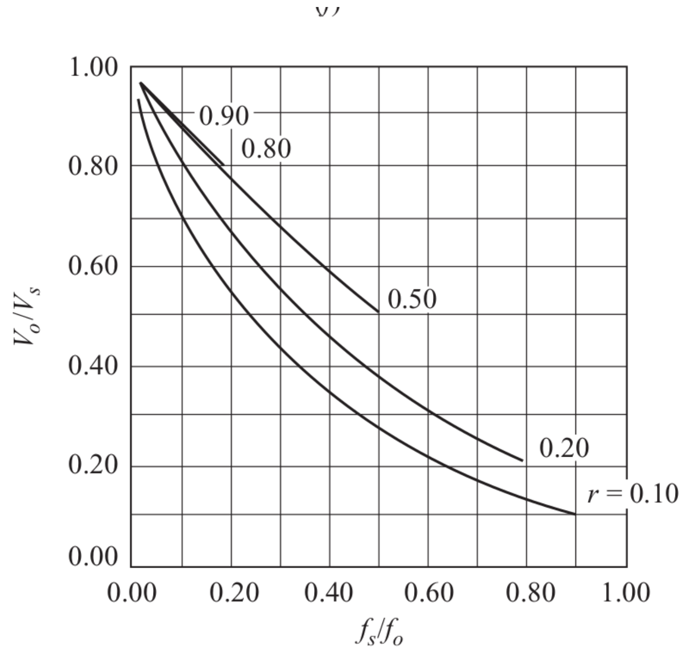
Output voltage is controlled by varying fs

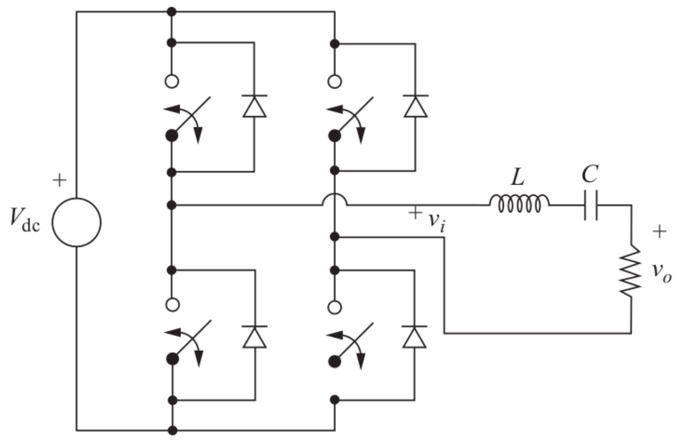
$V_o < V_s$, buck converter

Resonant Switch Converter: Zero Voltage Switching

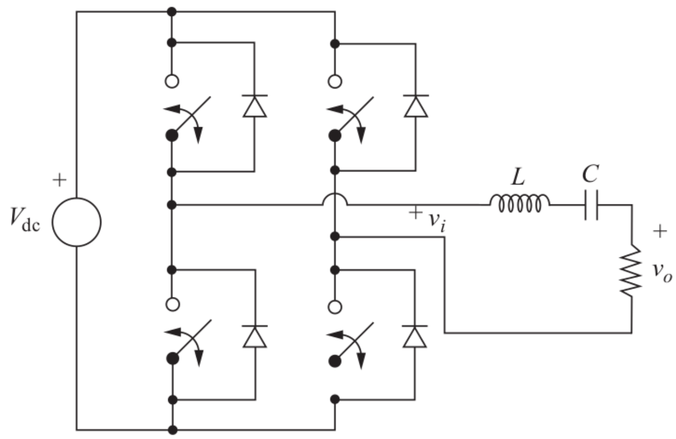


Output voltage is controlled by varying fs

Series Resonant Inverter



Series Resonant Inverter



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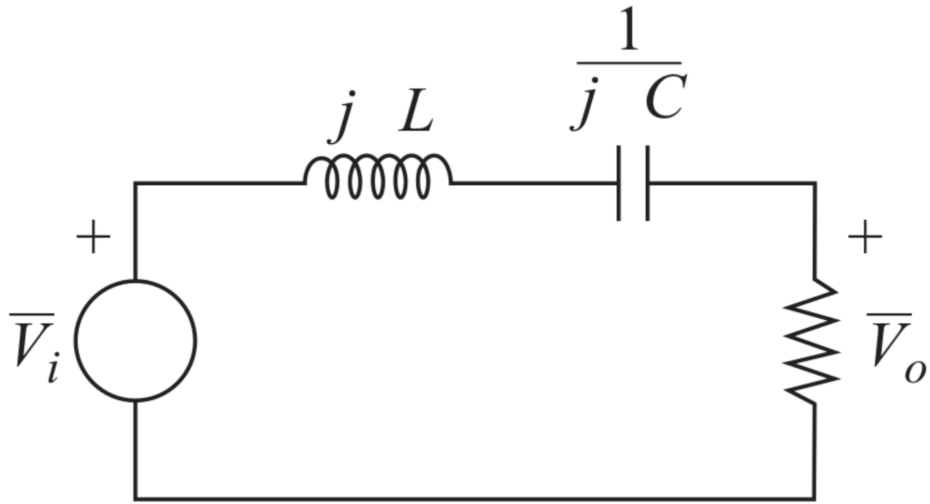
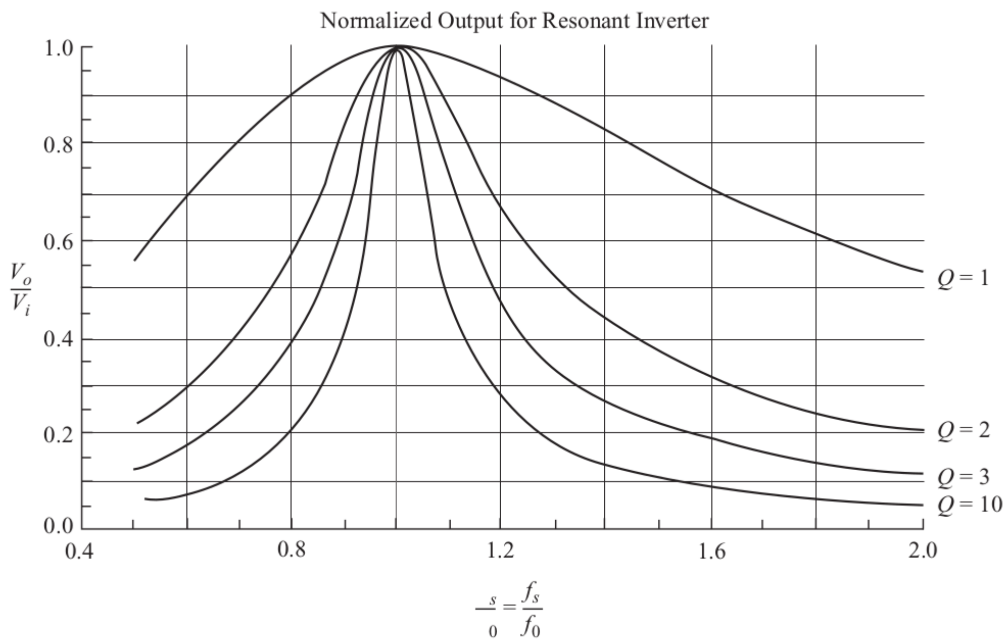


Phasor equivalent circuit

Series Resonant Inverter



Frequency Response

Series Resonant Converter

Series Resonant Converter

Add a diode rectifier to the output of the series resonant inverter

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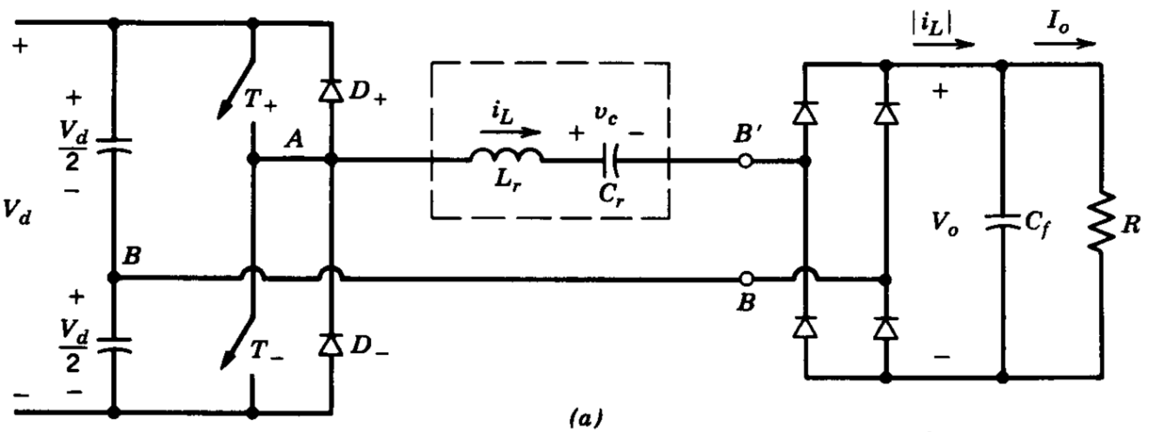

(a)

Variations of the Resonant Converters

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LLC Resonant Converter

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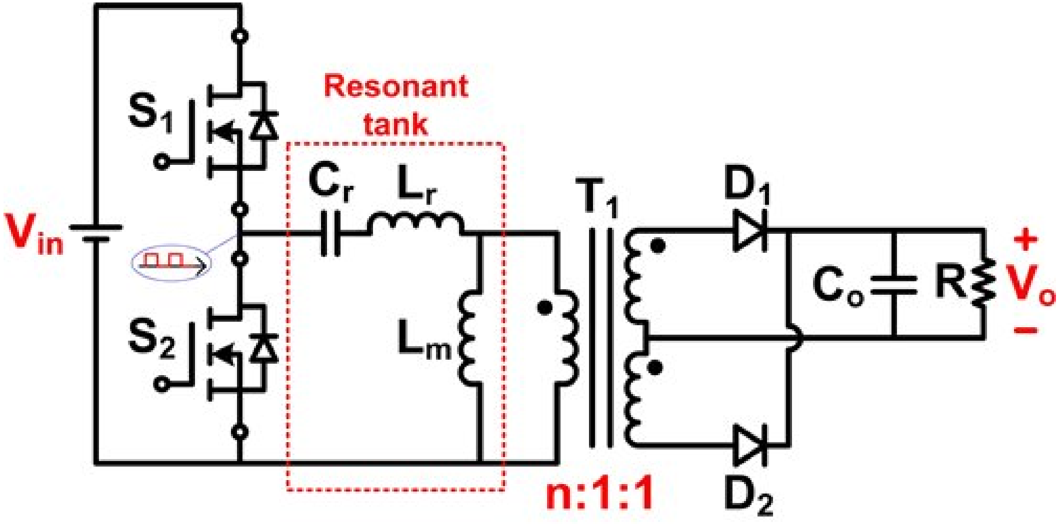
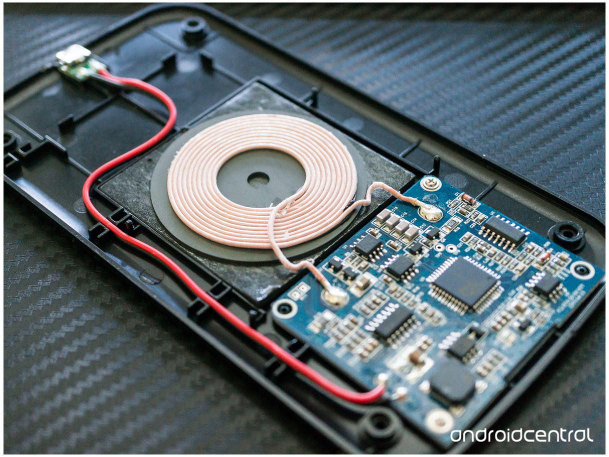
LLC Resonant Converter



Resonant Converter (Wireless Power Transfer)



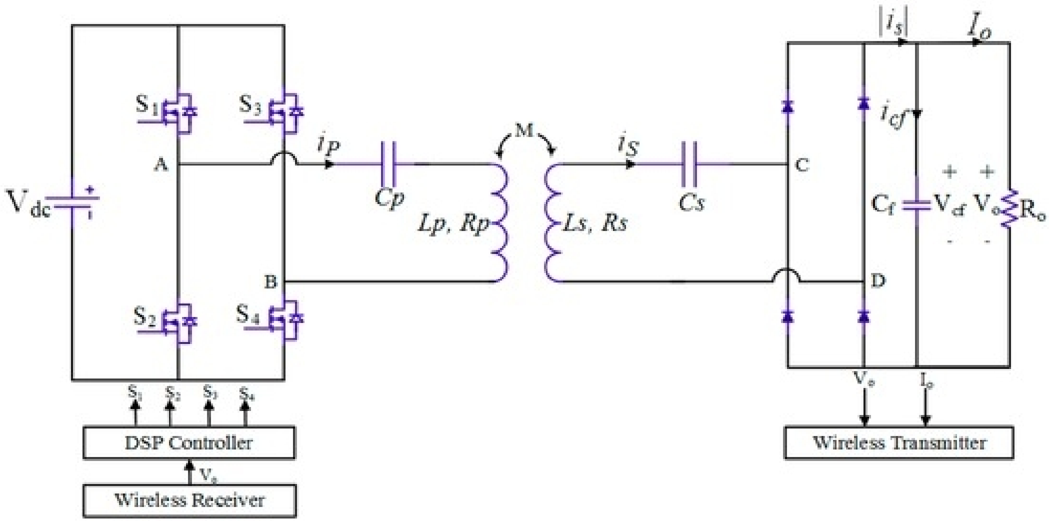
[Qi Wireless Charging]

[Multi-Coil Wireless Charger]

Resonant Converter (Wireless Power Transfer)

[BMW Electric Car Charger]

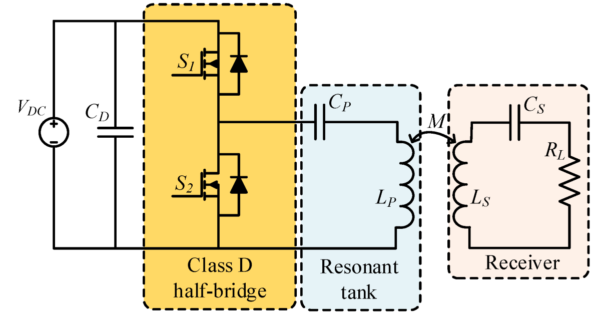
Resonant Converter (Wireless Power Transfer)



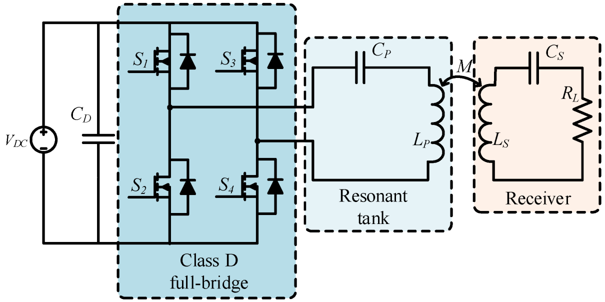
[Linearization and Control of Series-Series WPT]

Various Configurations

[For curious students: Overview of resonant circuits]



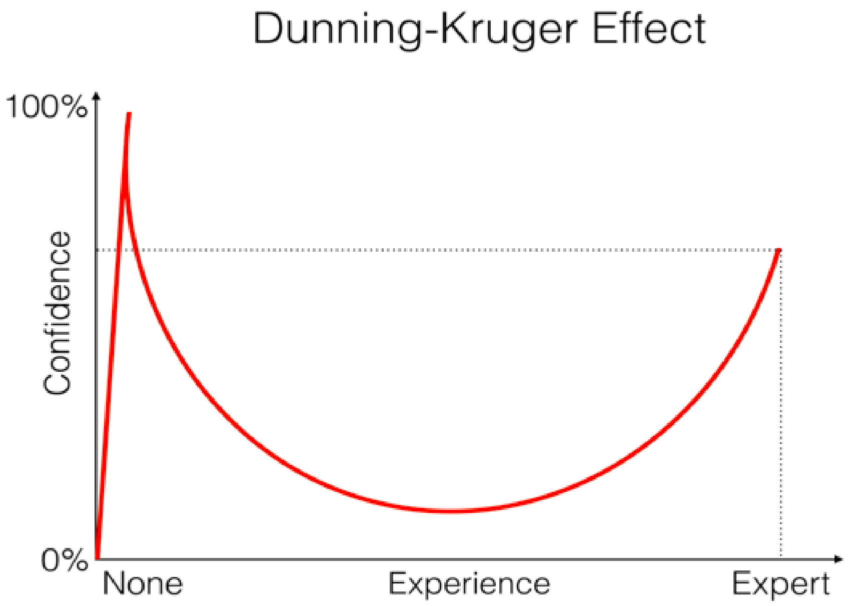
(a)



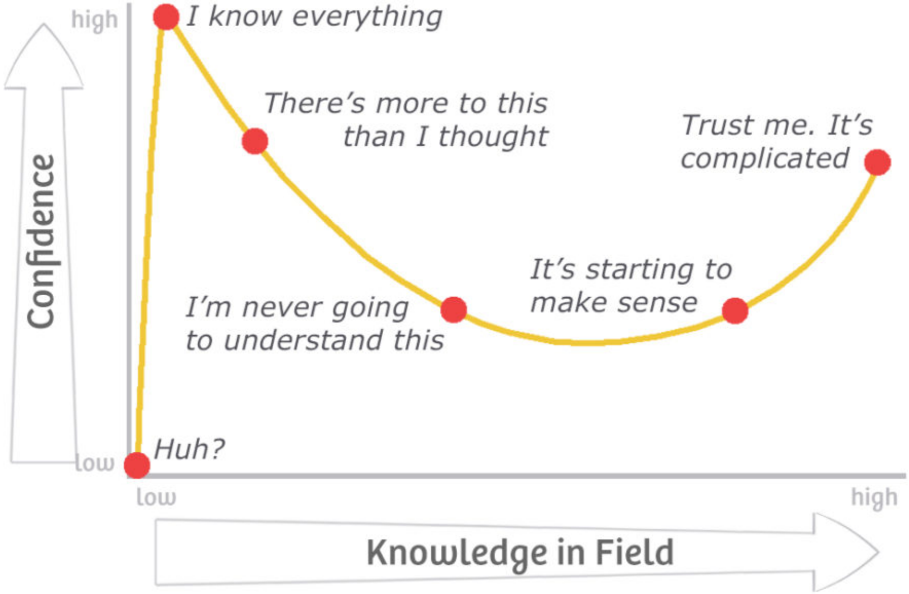
(b)

Dunning-Kruger Effect

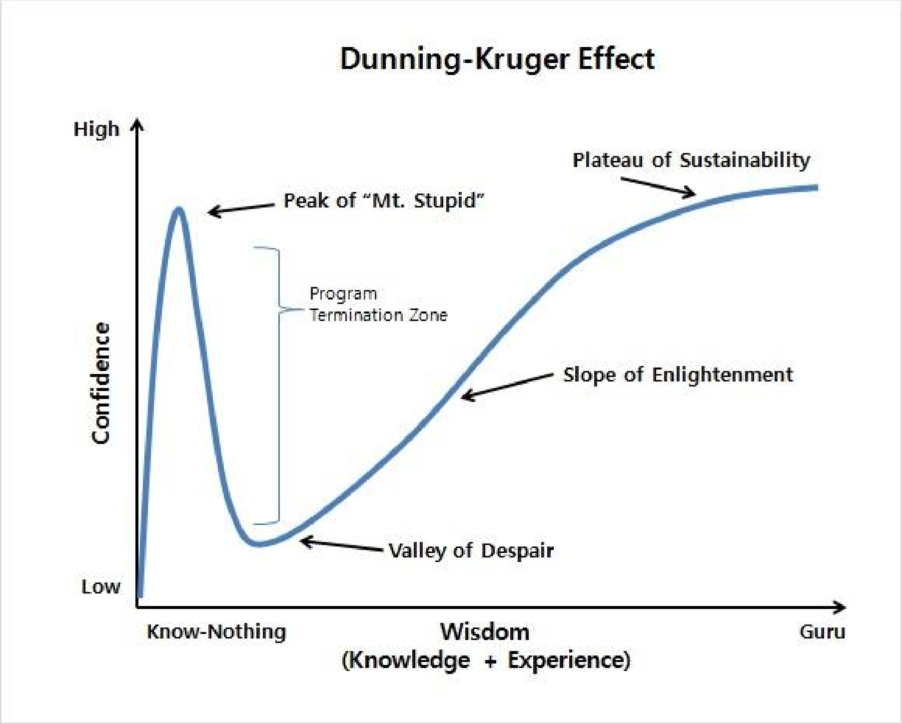
Dunning-Kruger Effect



Dunning-Kruger Effect



Dunning-Kruger Effect



Education in EEE

[ODTÜ Elektrik size neler kattı?]

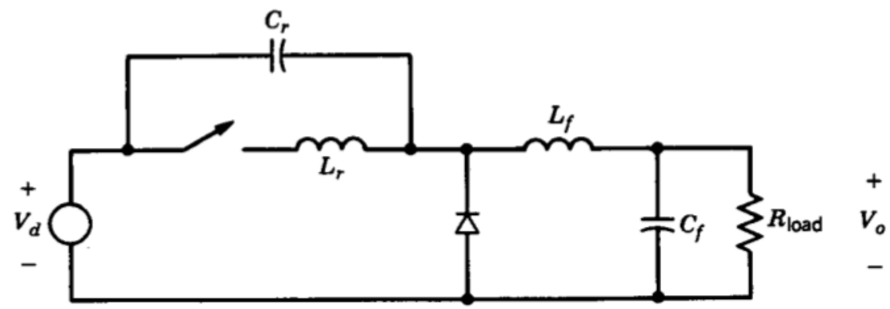
Drawing

You can download this presentation from:
keysan.me/ee464

Extras

Alternative ZCS Converter

Mohan Section 9.5



(a)

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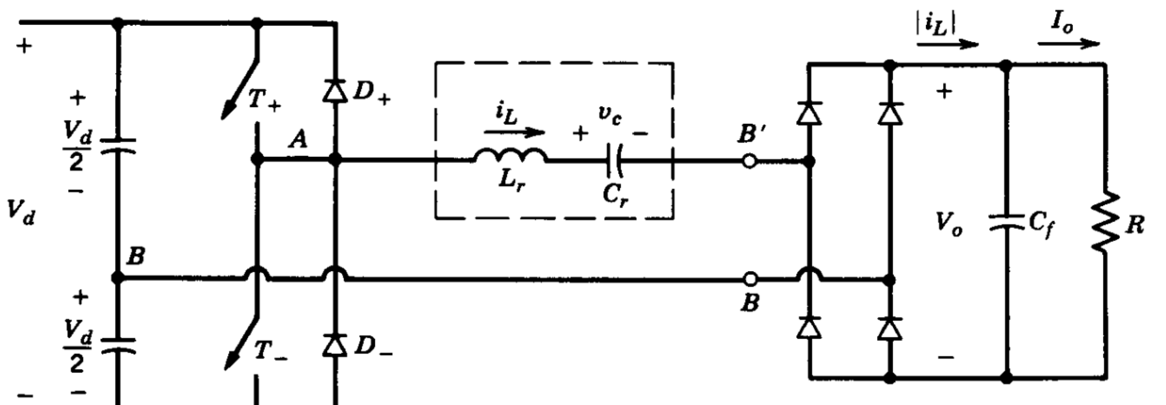


(a)

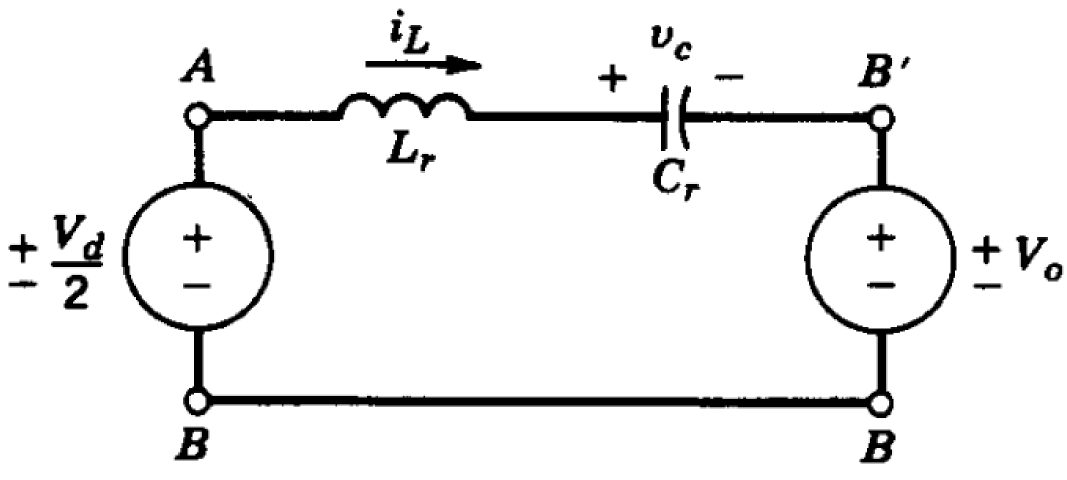
Series Resonant Converter

Series Resonant Converter

Simplified Equivalent Circuit

Series Resonant Converter

Simplified Equivalent Circuit



Series Resonant Converter

Continuous Conduction Mode with $\omega_s > \omega_0$

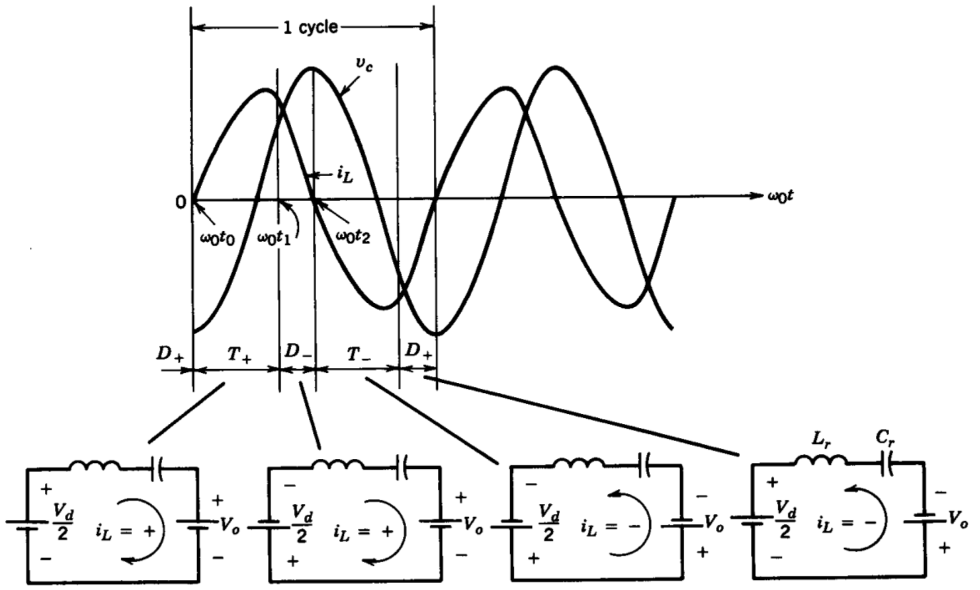


Figure 9-13 SLR dc–dc converter; continuous-conduction mode with $\omega_s > \omega_0$.

Series Resonant Converter

Continuous Conduction Mode with $\omega_s > \omega_0$

- iL is approximately sinusoidal
- Switches turn on at zero voltage (no turn-on losses)
- but they turn-off at non-zero current (turn-off losses exist)

Series Resonant Converter

Continuous Conduction Mode with $\omega_0/2 < \omega_s < \omega_0$

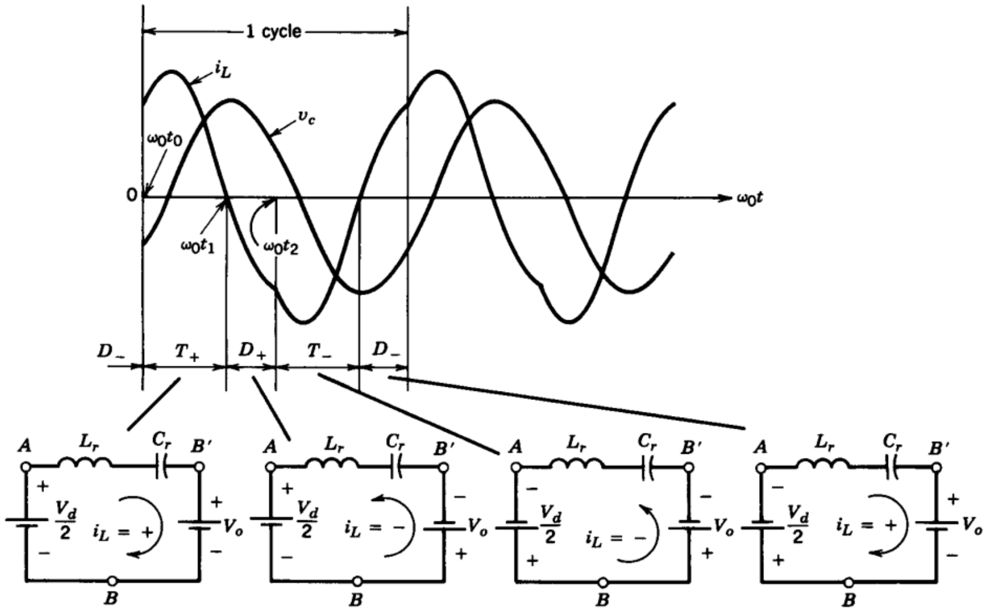


Figure 9-12 SLR dc–dc converter; continuous-conduction mode with $\frac{1}{2}\omega_0 < \omega_s < \omega_0$.

Series Resonant Converter

Continuous Conduction Mode with $\omega_0/2 < \omega_s < \omega_0$

- T+ conducts less than 180 degrees
- Switches turn on with finite voltage (turn-on losses exist)
- Switches turn-off with zero current (no turn-off losses)
- Turn-off occurs naturally, so thyristors can be used

Series Resonant Converter

Discontinuous Conduction Mode with $\omega_s < \omega_0/2$

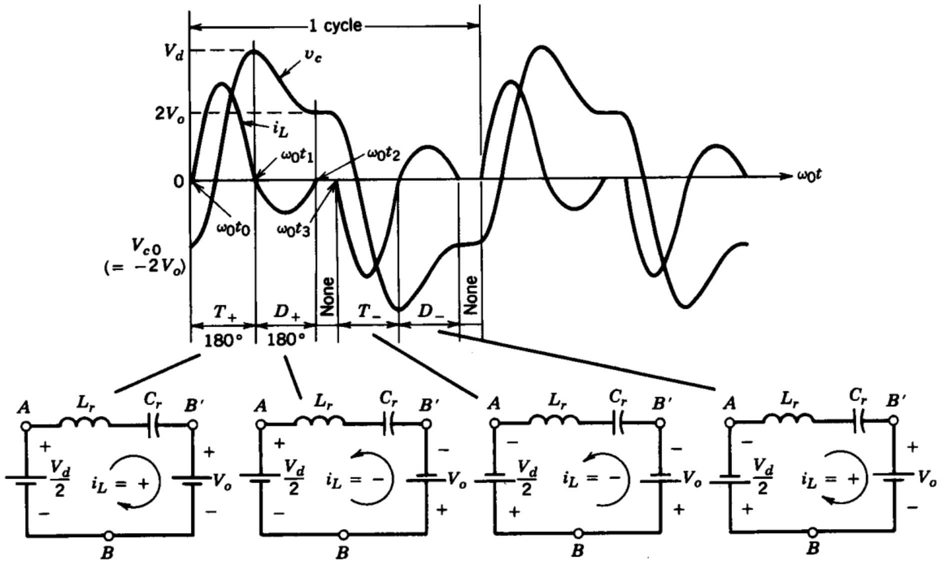


Figure 9-11 SLR dc–dc converter; discontinuous-conduction mode with $\omega_s < \frac{1}{2}\omega_0$.

Series Resonant Converter

Discontinuous Conduction Mode with $\omega_s < \omega_0/2$

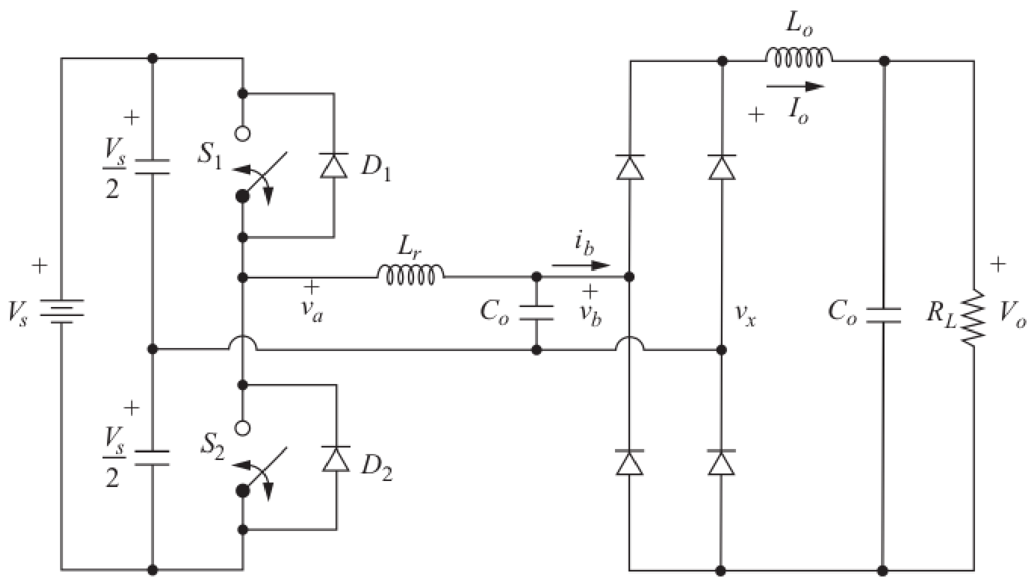
- iL is zero for some time (discontinuous conduction)
- Switches turn on at zero current, with finite voltage
- Switches turn-off naturally with zero current (no turn-off losses)
- Thyristors can be used
- Disadvantage: Relatively large peak current in the circuit

Variations of the Resonant Converters

Parallel Resonant Converter

Variations of the Resonant Converters

Parallel Resonant Converter

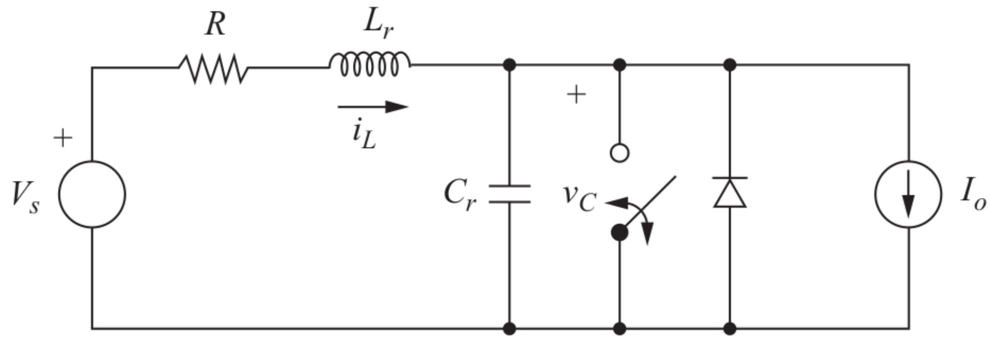


Variations of the Resonant Converters

Resonant DC Link Converter

Variations of the Resonant Converters

Resonant DC Link Converter



Variations of the Resonant Converters

3-Phase Resonant DC Link Converter

Variations of the Resonant Converters

3-Phase Resonant DC Link Converter