Electric Energy Conversion

6. DC/DC converters – part 2

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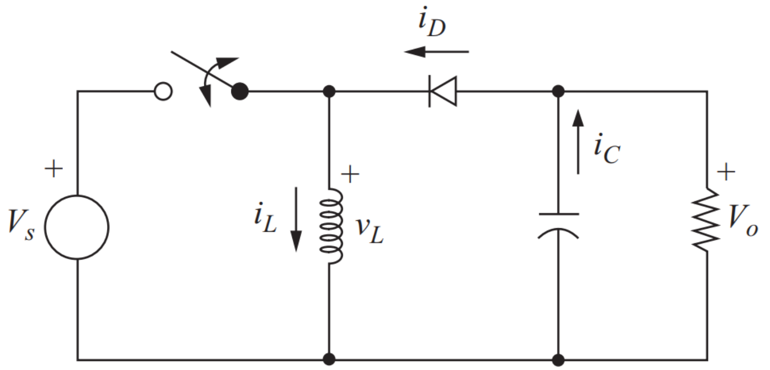
Outline

- Buck/Boost converters
- Bi-directional converters
- Simulation

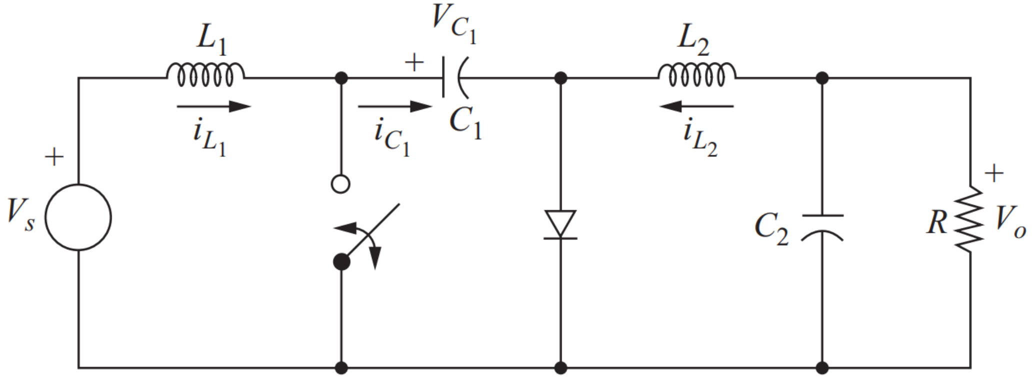
Buck/Boost converters

- In some applications it is necessary to generate a DC voltage that can be either **lower** or **greater** than the input. In these cases, we need to use buck/boost converters.
- There are several topologies:
- Both Buck/Boost and Cuk topologies have polarity reversal on the output voltage. The difference between them is that in Cuk, the energy transfer depends on capacitor C1 while in Buck/Boost depends on the inductor.
- The SEPIC has no polarity reversal on the output voltage.



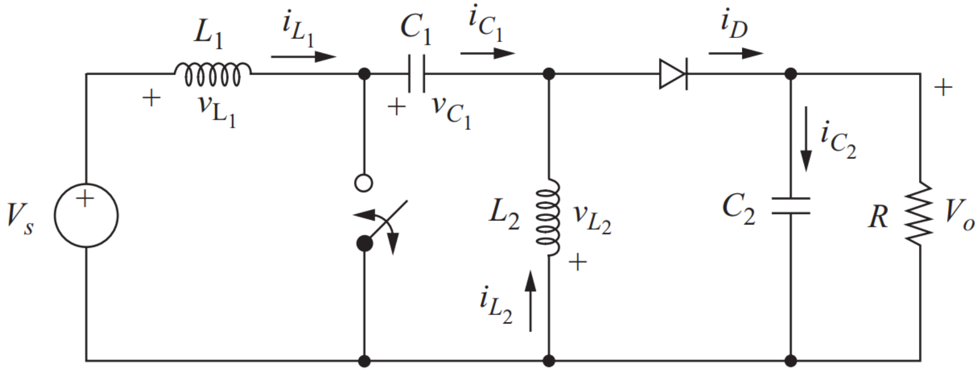
Buck/Boost

$$V_o = -V_s\left(\frac{D}{1-D}\right)$$



Cuk

$$V_o = -V_s\left(\frac{D}{1-D}\right)$$

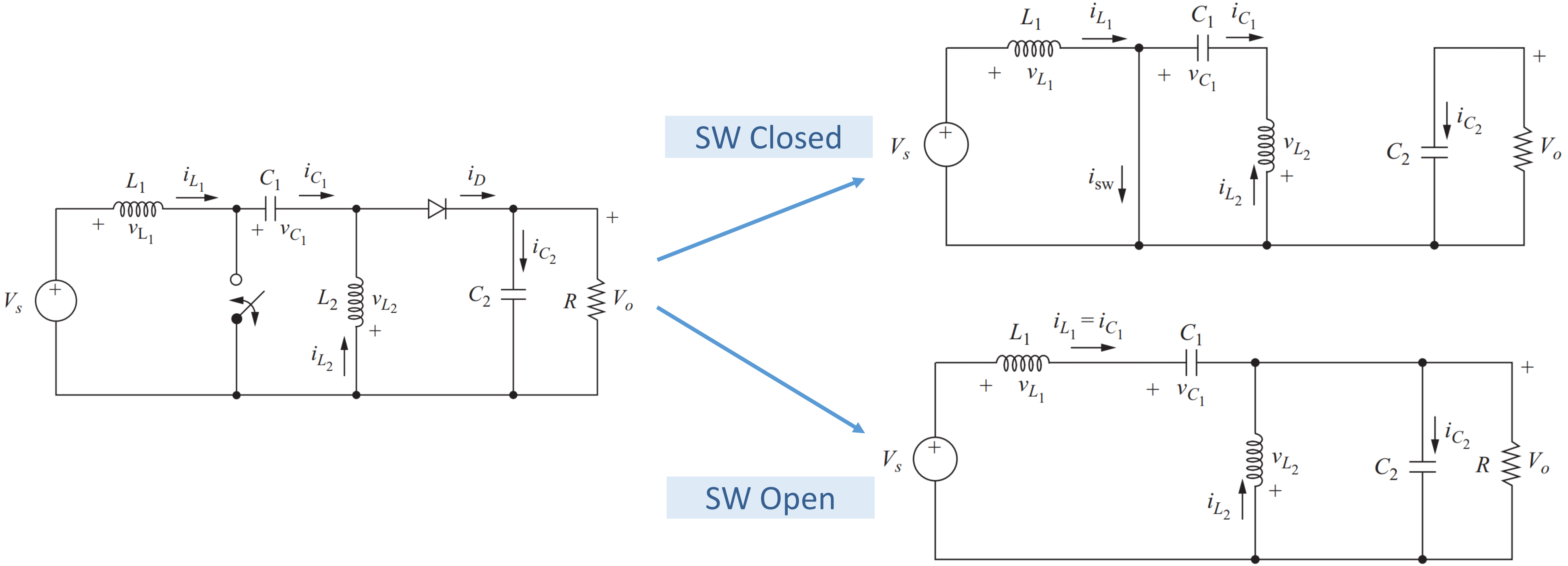


SEPIC

$$V_o = V_s\left(\frac{D}{1-D}\right)$$

SEPIC converter

- SEPIC means Single-Ended Primary Inductance Converter. It is an interesting topology because its output voltage can be either lower or greater than the input, without polarity reversal.



SEPIC converter

- Let's assume that the inductors and capacitors are big enough to provide continuous operation.
- We will also assume that the inductors and capacitors do not accumulate energy (point of equilibrium).
- Applying KVL around the path containing V_s, L_1, C_1 and L_2 gives:

$$-V_s + v_{L_1} + v_{C_1} - v_{L_2} = 0 \xrightarrow{\text{Taking the average}} -V_s + 0 + V_{C_1} - 0 = 0 \xrightarrow{\text{Hence}} V_{C_1} = V_s$$

- When the switch is closed (period DT), the diode is OFF and $v_{L1} = V_s$
- When the switch is open (period $(1-D)T$), the diode is ON and KVL around the the outer path gives

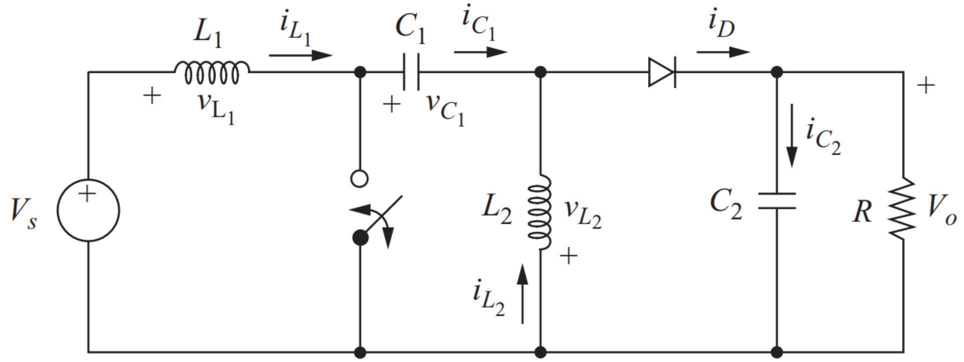
$$-V_s + v_{L_1} + v_{C_1} + V_o = 0 \xrightarrow{\text{Substituting } V_{C1} = V_s} -V_s + v_{L_1} + V_s + V_o = 0 \xrightarrow{\text{Hence}} v_{L1} = -V_o$$

- As the inductor does not accumulate energy:

$$(v_{L1,\text{ sw closed}})(DT) + (v_{L1,\text{ sw open}})(1-D)T = 0$$

$$\downarrow$$

$$V_s(DT) - V_o(1-D)T = 0 \longrightarrow \boxed{V_o = V_s\left(\frac{D}{1-D}\right)}$$



SEPIC converter

- To calculate the L_1 current ripples, we can use the conservation of power (neglecting losses):

$$P_s = P_o$$

$$P_s = V_s I_s = V_s I_{L1} \qquad P_o = V_o I_o$$

$$\xrightarrow{\text{Hence}} V_s I_{L1} = V_o I_o \longrightarrow I_{L1} = I_s = \frac{V_o I_o}{V_s} \quad \text{(average value)}$$

- Now, as we know that when the switch is closed $v_{L1} = V_s$

$$v_{L1} = V_s = L_1\left(\frac{di_{L1}}{dt}\right) = L_1\left(\frac{\Delta i_{L1}}{\Delta t}\right) = L_1\left(\frac{\Delta i_{L1}}{DT}\right) \xrightarrow{\text{Hence}} \Delta i_{L1} = \frac{V_s DT}{L_1} = \frac{V_s D}{L_1 f} \quad \text{(ripple)}$$

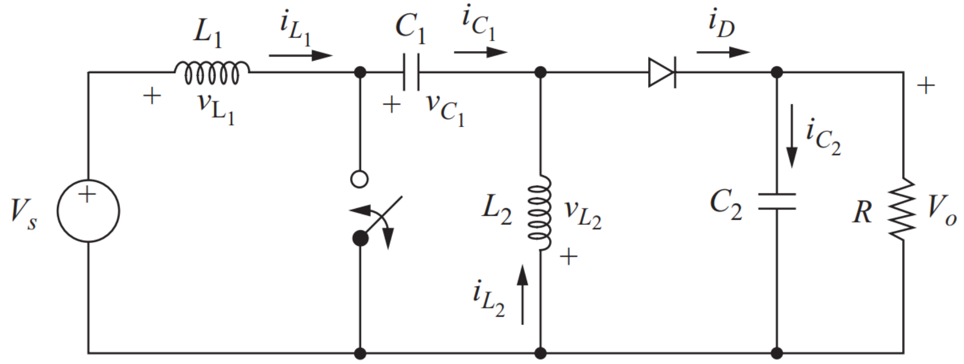
- A similar analysis can be done for L_2, using KCL, resulting in:

$$I_{L2} = I_o$$

(average value)

$$\Delta i_{L2} = \frac{V_s DT}{L_2} = \frac{V_s D}{L_2 f}$$

(ripple)



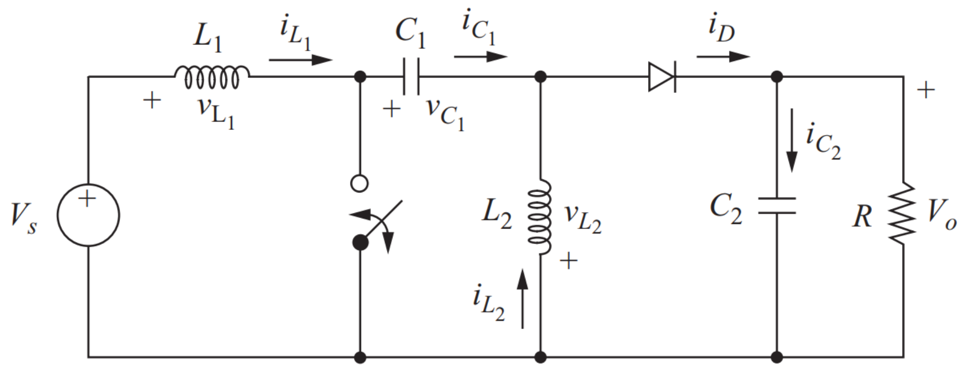
SEPIC converter

- To calculate the C_2 voltage ripple we can use the fact that the output stage composed of a diode, capacitor and load is exactly the same as a Boost converter, so the same relations apply for C_2.

$$\boxed{\Delta V_o = \Delta V_{C2} = \frac{V_o D}{R C_2 f}} \longrightarrow \boxed{C_2 = \frac{D}{R(\Delta V_o / V_o) f}}$$

- To calculate the C_1 voltage ripple we use the same steps as done before, deriving the ripple from its charge:

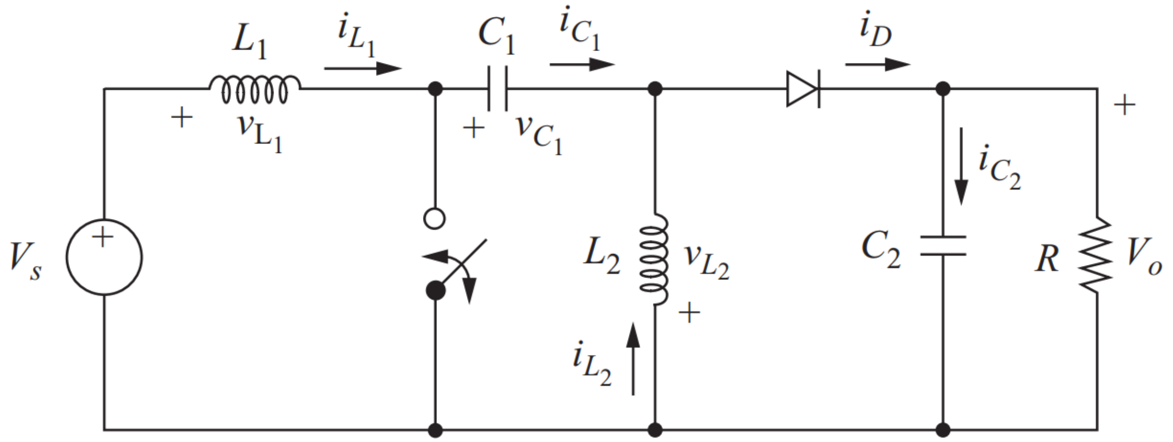
$$\boxed{\Delta V_{C_1} = \frac{V_o D}{R C_1 f}} \longrightarrow \boxed{C_1 = \frac{D}{R(\Delta V_{C_1} / V_o) f}}$$



SEPIC converter - Exercise

- For the SEPIC converter below, determine (consider ideal components):

1. output voltage
2. average, maximum and minimum inductor currents
3. voltage ripple across each capacitor.



- Data

$$V_s = 9\ \text{V}$$
$$D = 0.4$$
$$f = 100\ \text{kHz}$$
$$L_1 = L_2 = 90\ \mu\text{H}$$
$$C_1 = C_2 = 80\ \mu\text{F}$$
$$I_o = 2\ \text{A}$$

- Key equations

$$V_o = V_s\left(\frac{D}{1-D}\right)$$

$$I_{L1} = \frac{V_o I_o}{V_s} \qquad \Delta i_{L1} = \frac{V_s D}{L_1 f} \qquad \Delta V_{C_2} = \frac{V_o D}{R C_2 f}$$

$$I_{L2} = I_o \qquad \Delta i_{L2} = \frac{V_s D}{L_2 f} \qquad \Delta V_{C_1} = \frac{V_o D}{R C_1 f}$$

SEPIC converter - Exercise

- Solution

$$V_o = V_s\left(\frac{D}{1-D}\right) = 9\left(\frac{0.4}{1-0.4}\right) = 6 \text{ V}$$

$$I_{L_1} = \frac{V_o I_o}{V_s} = \frac{6(2)}{9} = 1.33 \text{ A}$$

$$\Delta i_{L_1} = \frac{V_s D}{L_1 f} = \frac{9(0.4)}{90(10)^{-6}(100{,}000)} = 0.4 \text{ A}$$

Maximum and minimum currents in L_1 are then

$$I_{L1,\max} = I_{L_1} + \frac{\Delta i_{L1}}{2} = 1.33 + \frac{0.4}{2} = 1.53 \text{ A}$$

$$I_{L1,\min} = I_{L_1} - \frac{\Delta i_{L1}}{2} = 1.33 - \frac{0.4}{2} = 1.13 \text{ A}$$

For the current in L_2, the average is the same as the output current $I_o = 2$ A. The variation in I_{L_2} is determined from

$$\Delta i_{L_2} = \frac{V_s D}{L_2 f} = \frac{9(0.4)}{90(10)^{-6}(100{,}000)} = 0.4 \text{ A}$$

resulting in maximum and minimum current magnitudes of

$$I_{L2,\max} = 2 + \frac{0.4}{2} = 2.2 \text{ A}$$

$$I_{L2,\min} = 2 - \frac{0.4}{2} = 1.8 \text{ A}$$

Using an equivalent load resistance of 6 V/2 A = 3 Ω, the ripple voltages in the capacitors are determined from

$$\Delta V_o = \Delta V_{C_2} = \frac{V_o D}{R C_2 f} = \frac{6(0.4)}{(3)80(10)^{-6}(100{,}000)} = 0.1 \text{ V}$$

$$\Delta V_{C_1} = \frac{V_o D}{R C_1 f} = \frac{6(0.4)}{(3)80(10)^{-6}(100{,}000)} = 0.1 \text{ V}$$

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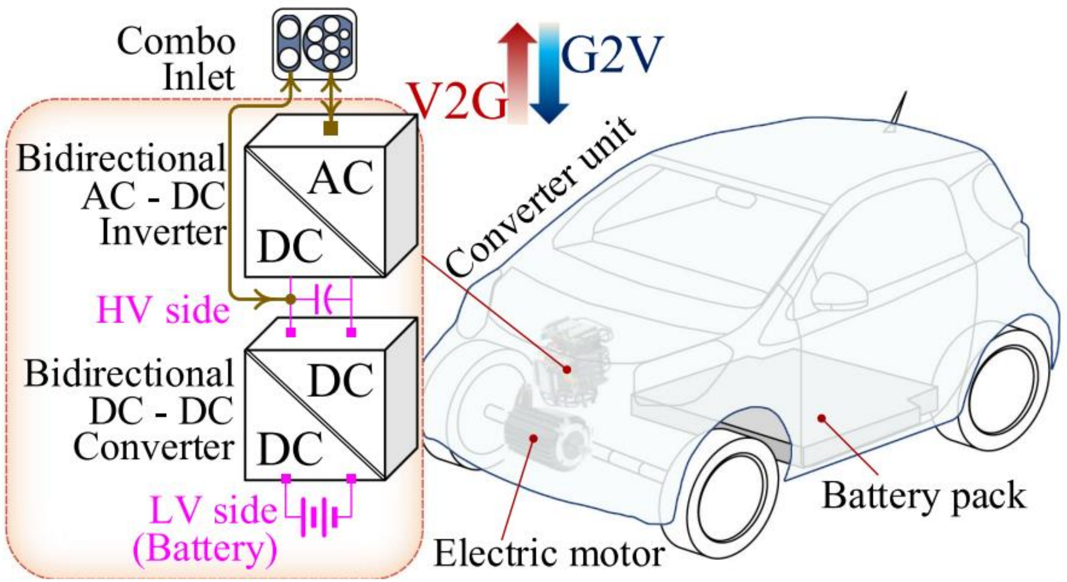
Bi-directional DC/DC converters

- In some industrial applications, it is required to exchange DC power in two directions.
- In these cases, the DC/DC converter must be **bidirectional** (the current can be reversed).
- This is common in **V2G** applications and **energy storage** applications.

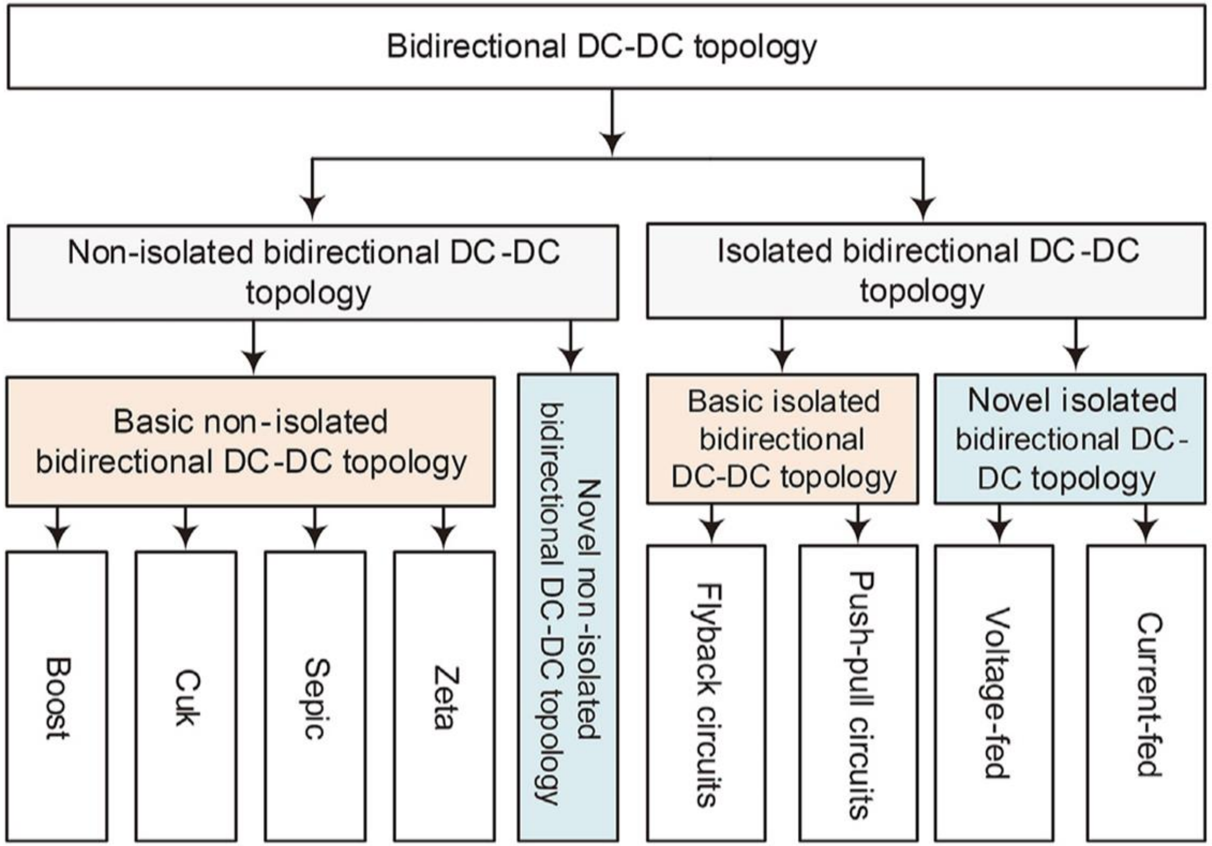


Layout of an EV electrical system.

Source: H. Heydari-doostabad and T. O’Donnell, “A Wide-Range High-Voltage-Gain Bidirectional DC–DC Converter for V2G and G2V Hybrid EV Charger,” IEEE Transactions on Industrial Electronics, vol. 69, no. 5, pp. 4718–4729, May 2022, doi: 10.1109/tie.2021.3084181.

Bi-directional DC/DC converters

- There are many topologies of DC/DC converters. Most of them replace diodes with transistors to allow current flow in both directions.



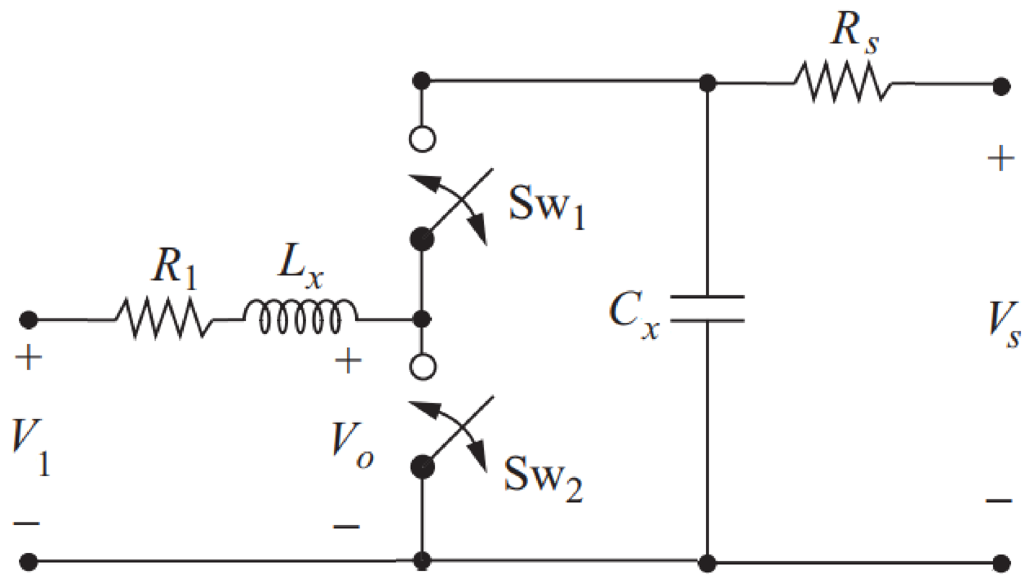
Source: J. Wang, B. Wang, L. Zhang, J. Wang, N. I. Shchurov, and B. V. Malozyomov, "Review of bidirectional DC–DC converter topologies for hybrid energy storage system of new energy vehicles," Green Energy and Intelligent Transportation, vol. 1, no. 2, p. 100010, Sep. 2022, doi: 10.1016/j.geits.2022.100010.

Bi-directional Buck converter

- The bi-directional buck converter has the same principle of operation of a buck converter, but uses two switches to allow current flowing in both directions.
- The topology with two switches is known as a **synchronous buck converter.**
- The switches 1 and 2 are complementary: when one if ON, the other is OFF, and vice versa.
- The switches can be MOSFETs in low-power applications or IGBTs in medium/high-power applications.

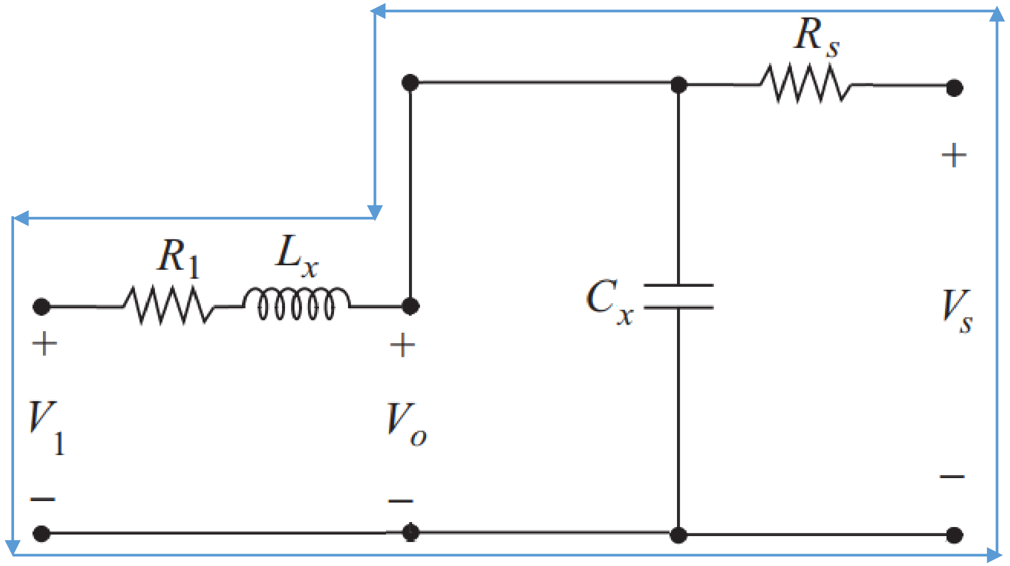
$$V_o = V_s D$$

The direction of the current will be defined by the difference between V_1 and V_0

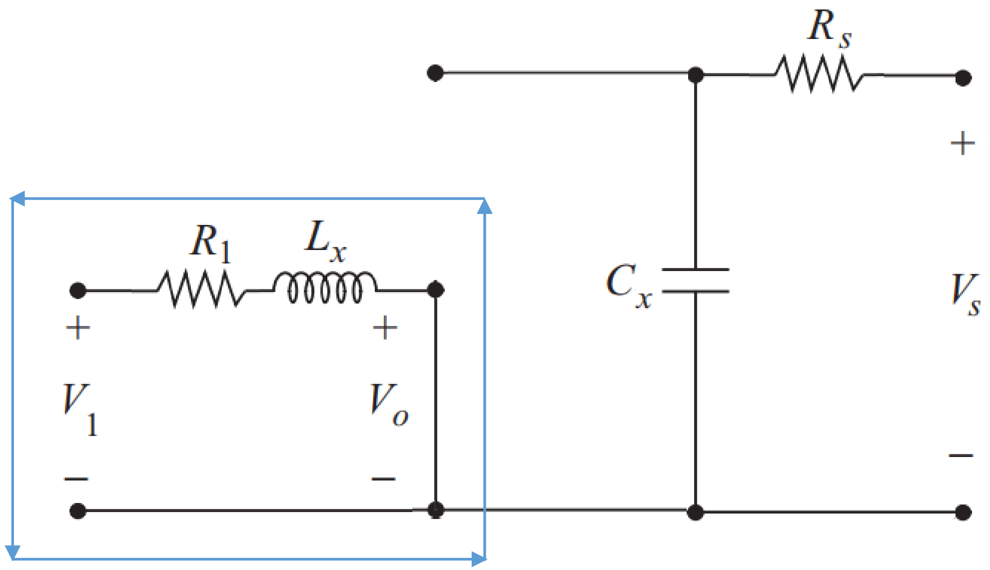


Bi-directional Buck converter

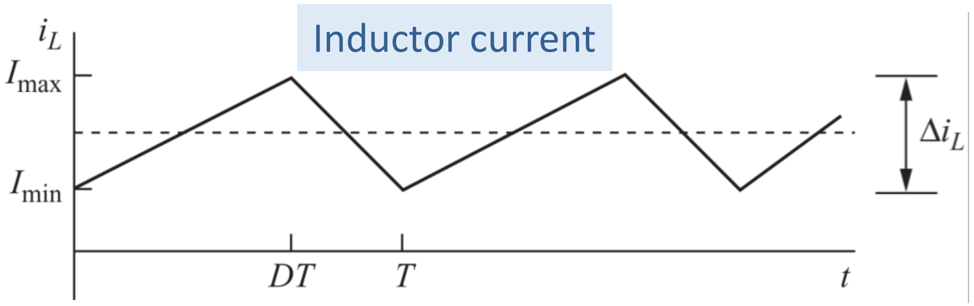
- **When SW_1 is closed and SW_2 is open:**
- Energy is stored in L_x



- **When SW_2 is closed and SW_1 is open:**
- Energy is released by L_x



If L_x is too big, the current dynamics are slower



- To have continuous current:

$$L = \left(\frac{V_s - V_o}{\Delta i_L f}\right) D = \frac{V_o(1 - D)}{\Delta i_L f}$$

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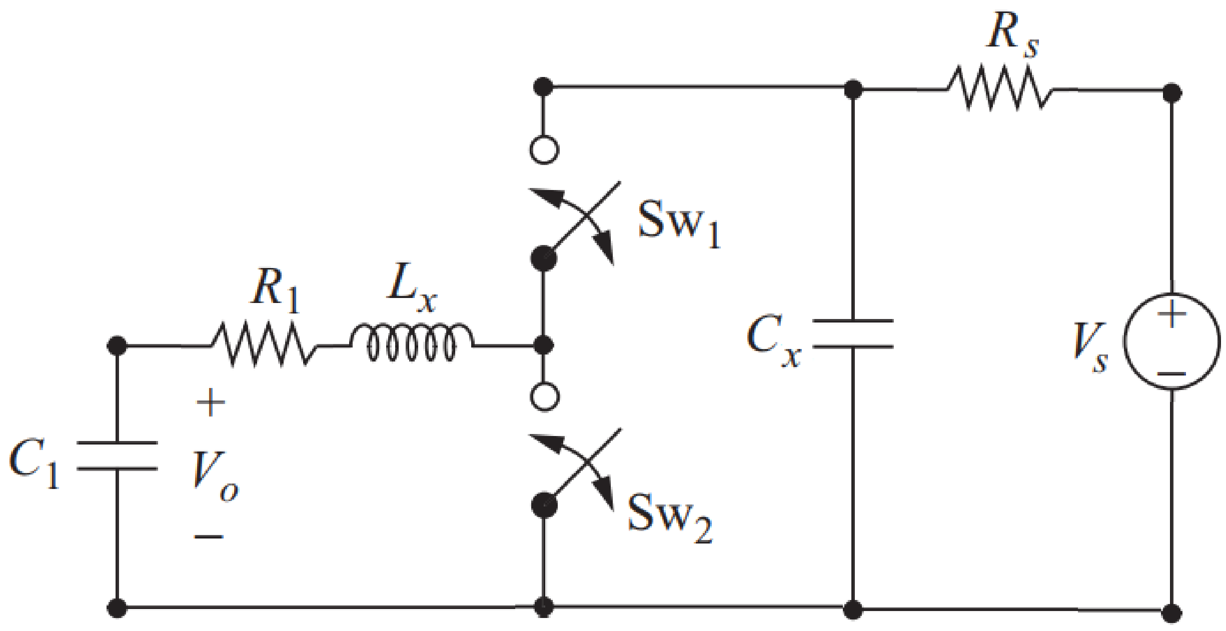
Simulation

- Simulate a bi-directional DC/DC converter.

Data:

- Vs = 1000 V (DC) (Rs=1 mOhm)
- L = 50 uH (R1=1 mOhm)
- Cx = 50 uF
- C1 = 5 F (initally charged to 500 V)
- f = 10 kHz
- Start with D = 0.5



a) Define D = 0.8 and then D = 0.3 and plot the power exchanged and C1 voltage

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