Power Electronics

CHOPPERS

2018

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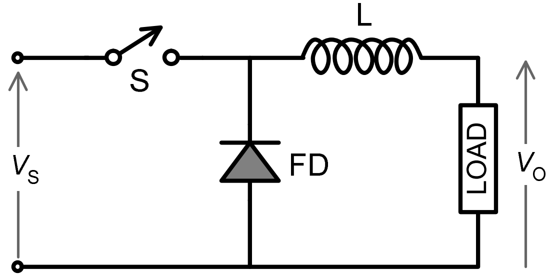
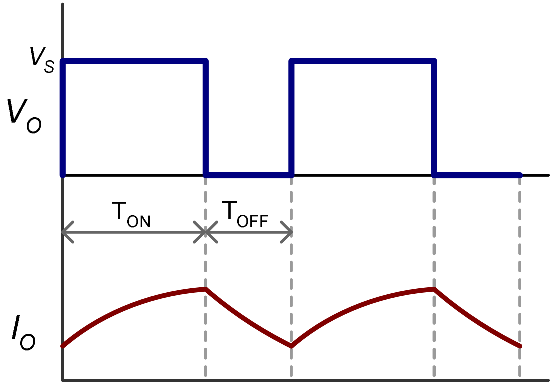
Choppers

- It is a DC-DC converter
- It can be step up chopper or step down chopper

Step-down Chopper (Buck converter)





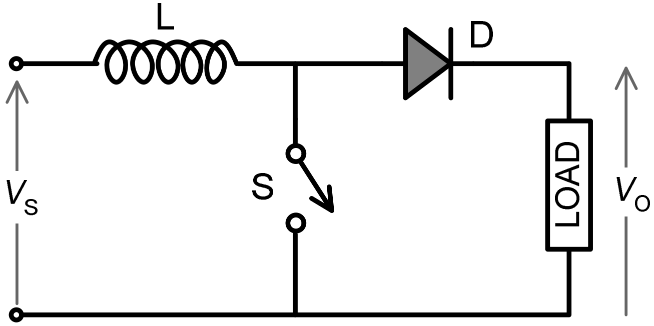
Averege output, $V_O = V_S \dfrac{T_{ON}}{T_{ON}+T_{OFF}} = V_S \times \alpha$

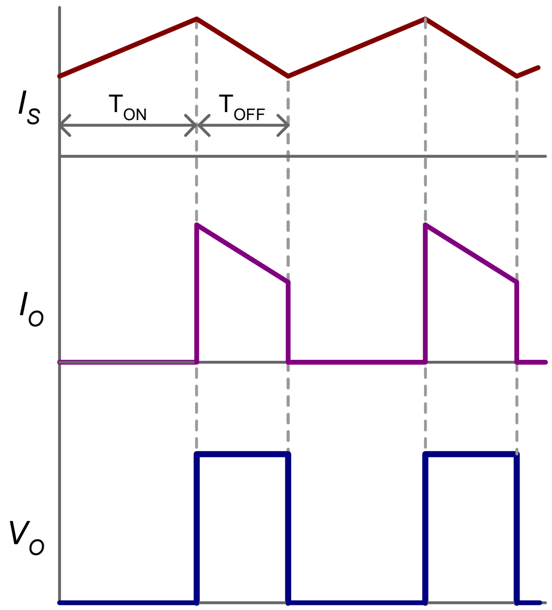
α is the *duty cycle*, which is equal to $\dfrac{T_{ON}}{T_{ON}+T_{OFF}}$

$$V_{O(RMS)} = \sqrt{V_S^{\,2} \frac{T_{ON}}{T_{ON}+T_{OFF}}} = \sqrt{V_S^{\,2} \times \alpha} = V_S \sqrt{\alpha}$$

- Switching is done at chopping frequency, typically 5 kHz to 25 kHz
- SCR, GTO, BJT, MOSFET or IGBT can be used as switch
- MOSFET and IGBT are preferred as switch for common applications since special commutation circuits are not required.

Step-up Chopper (Boost Converter)

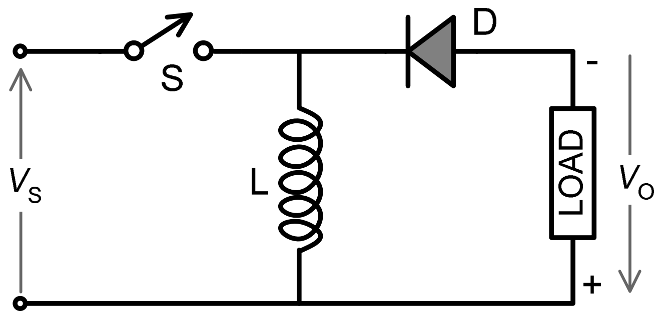




Averege output, $V_O = V_S \dfrac{1}{1-\alpha}$

α is the *duty cycle*, which is equal to $\dfrac{T_{ON}}{T_{ON}+T_{OFF}}$, *ie* $\alpha = \dfrac{T_{ON}}{T}$

Buck-Boost Converter



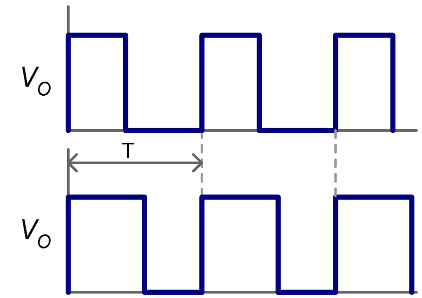
$$\text{Averege output, } V_O = V_S \frac{\alpha}{1-\alpha}$$

$$\alpha \text{ is the } \textit{duty cycle}, \ \alpha = \frac{T_{ON}}{T}$$

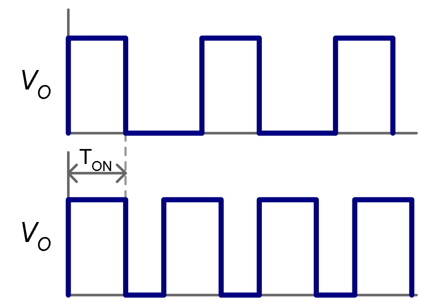
- Output polarity is different when compared to buck or boost converter
- For 0 < α < 0.5 step down operation is achieved
- For 0.5 < α < 1.0 step up operation is achieved

Control Strategies

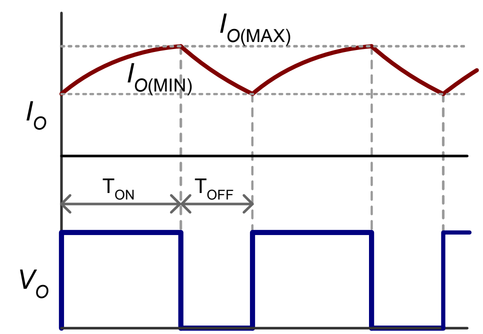
- **Time Ratio Control**
  - **PWM Control**
    (Frequency is constant and pulse width is controlled)



  - **Variable Frequency Control**
    (Pulse width is constant and frequency is controlled)

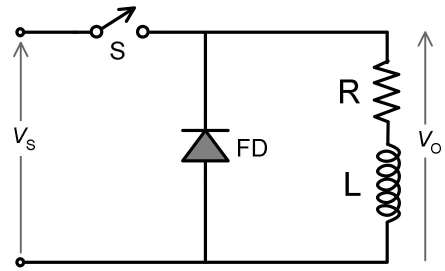


- **Current Limit Control**
  (Switching is done at upper limit and lower limit of output current)



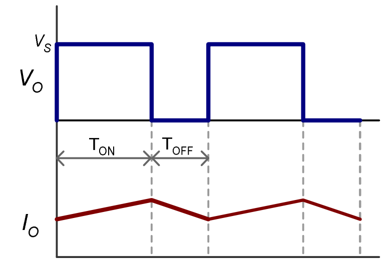
Example

A DC chopper connected to a 120 V source supplies to an inductive load of 30 mH in series with a 6 Ω resistance. A freewheeling diode is connected across the load. The load current varies between 10A and 12A. Determine the duty cycle of chopper.



$$\text{Average value of load current} = \frac{10+12}{2} = 11\text{ A}$$

$$\text{Maximum value of load current} = \frac{120}{6} = 20\text{ A}$$

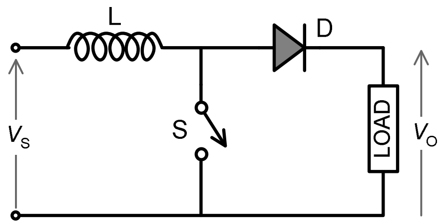


$$\text{Average value of ouput voltage} = 120 \times \frac{11}{20} = 66\text{ V}$$

$$\text{Duty Cycle} = \frac{T_{ON}}{T_{ON}+T_{OFF}} = \frac{V_O}{V_S} = \frac{66}{120} = 0.55$$

Example

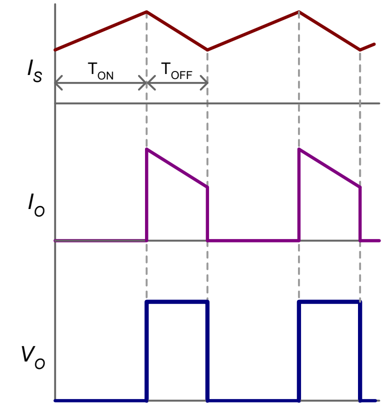
A step-up chopper is used to generate 220 V from 100 V dc source. The blocking period of switch is 80µs. Compute the required pulse width.



Output voltage, $V_O = V_S \dfrac{1}{1-\alpha}$

$$220 = 100 \frac{1}{1-\alpha}$$

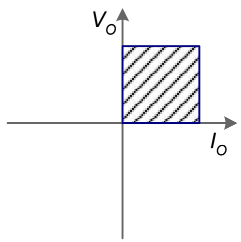
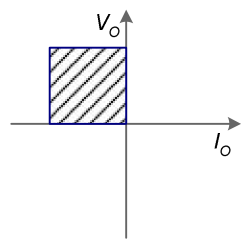
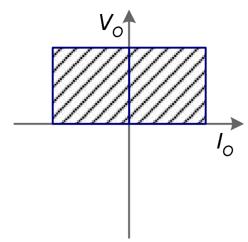
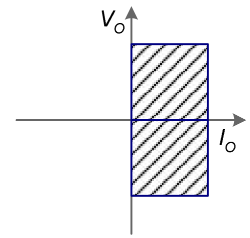
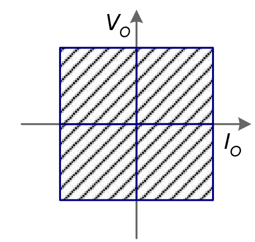
then, $\alpha = 0.5454$



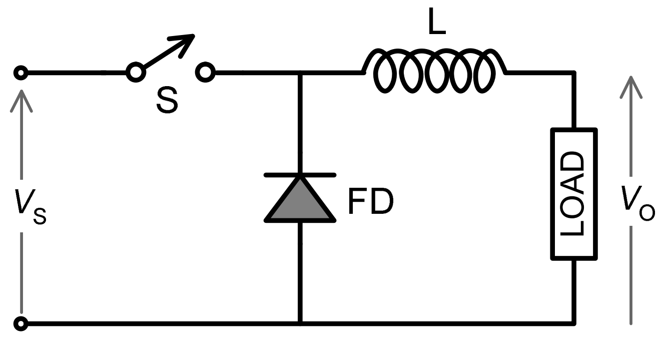
Duty cycle, $\alpha = \dfrac{T_{ON}}{T_{ON} + T_{OFF}}$

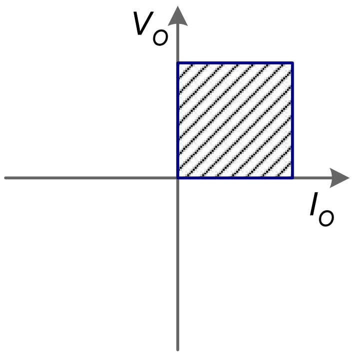
$$0.5454 = \frac{T_{ON}}{T_{ON} + 80} \Rightarrow T_{ON} = 96\ \mu s$$

Chopper Classification

Type ->	Class A	Class B	Class C	Class D	Class E
Quadrants					
Output Polarity	Voltage: + Current: +	Voltage: + Current: -	Voltage: + Current: ±	Voltage: ± Current: +	Voltage: ± Current: ±
Typical Application	DC Motor operation	Regenerative braking of DC motor	Both motoring and regenerative braking of DC motor	Both motoring and regenerative braking of DC motor	Reversible regenerative motor drive

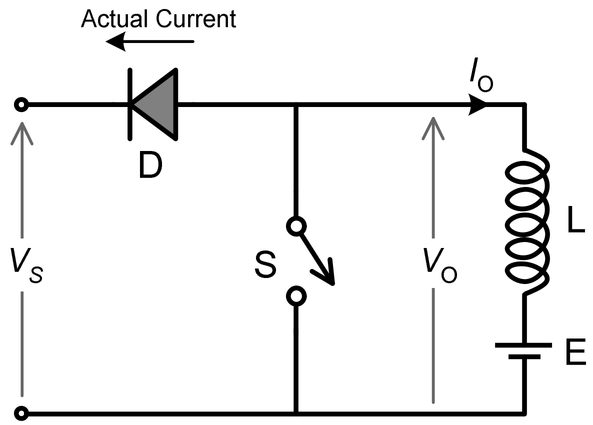
Type A Chopper

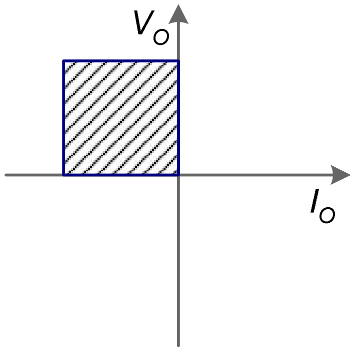




- Average value of both voltage and current are positive
- This chopper is also called step down chopper
- Freewheeling diode FD maintains the current when switch S is off
- Power flow is always from Source to Load

Type B Chopper



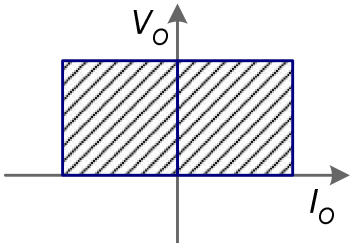


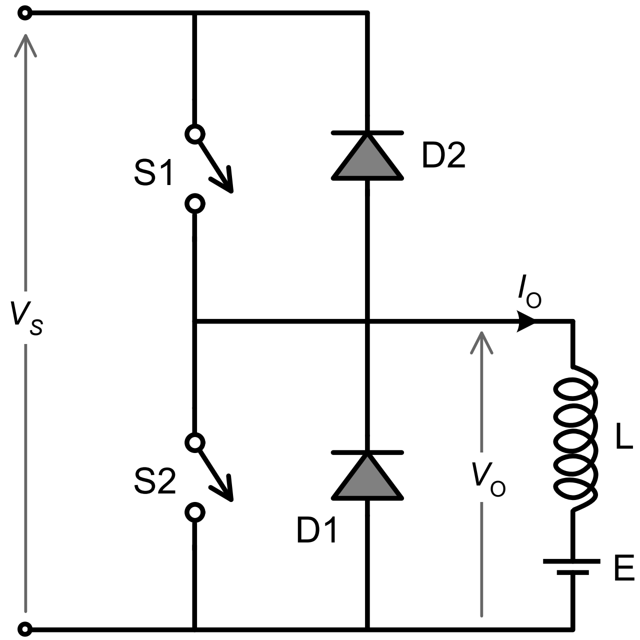
$$\text{Load voltage, } V_O = E + L\frac{di}{dt}$$

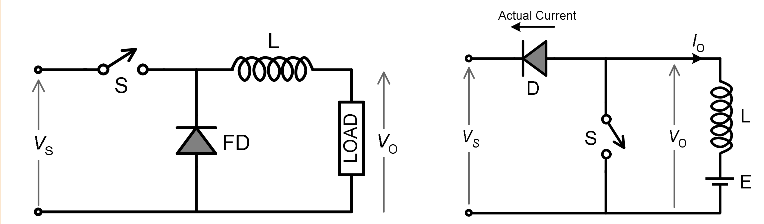
V_O may be more than V_S and make diode D forward biased

- The load should have a battery source or it may be a motor which has back emf
- Average value of voltage is positive but current is negative
- This chopper is also called step up chopper
- Power flow is from Load to Source

Type C Chopper



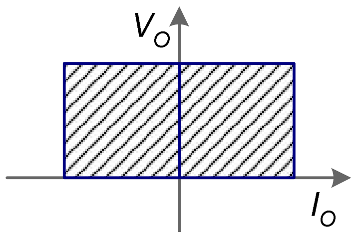




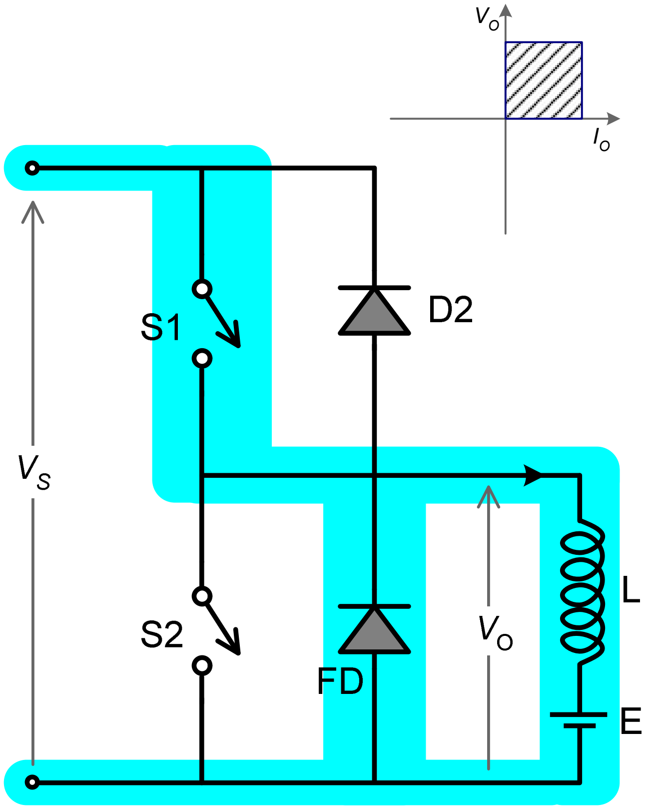
Is a combination of
Type A and Type B Choppers

- Average value of voltage is positive but current may be positive or negative
- Switches S1 and S2 should not be turned on at the same time
- Power flow may be in either direction
- Used for motoring and regenerative braking of dc motors

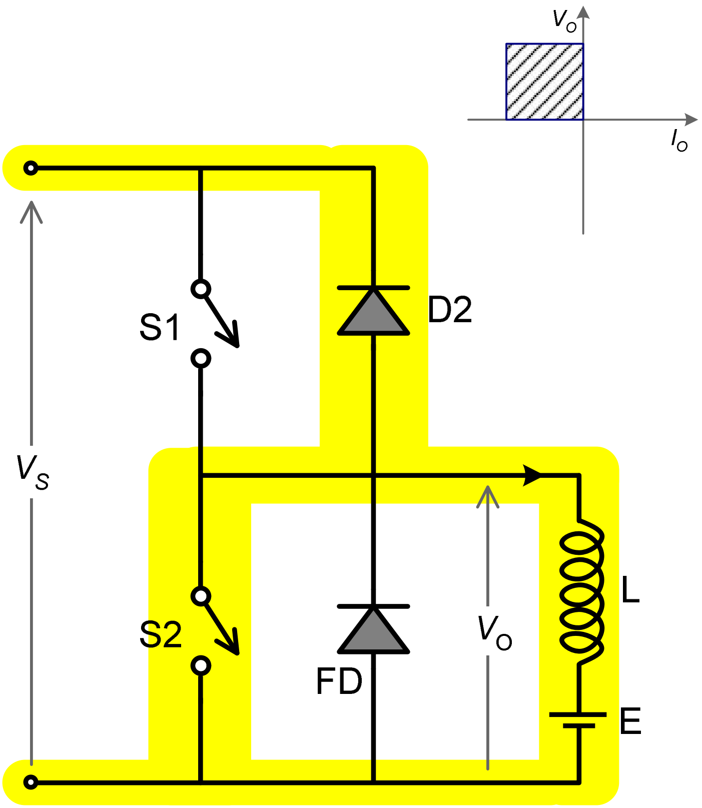
Type C operating modes



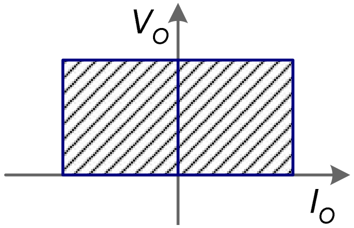
Type A operation:

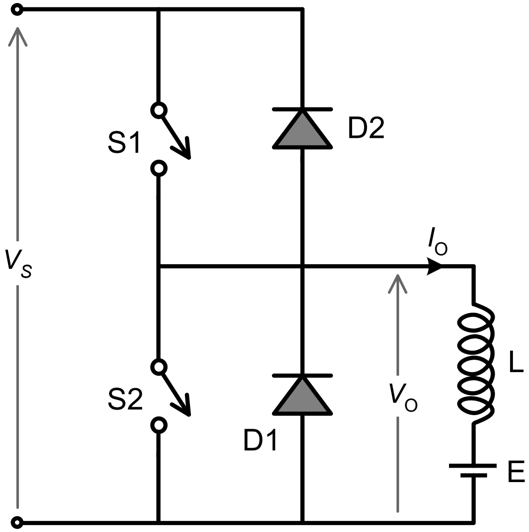


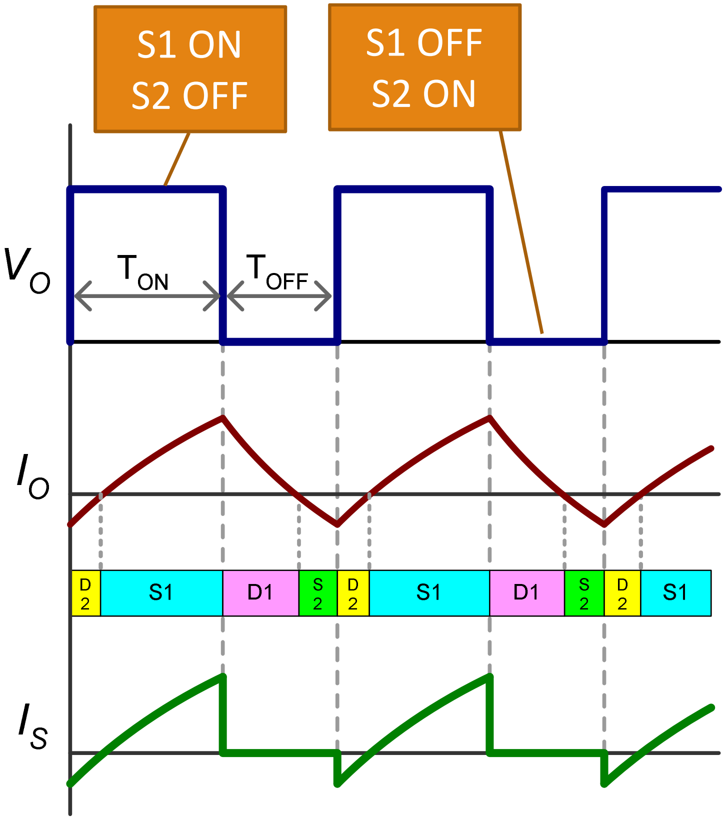
Type B operation:



Type C Waveforms

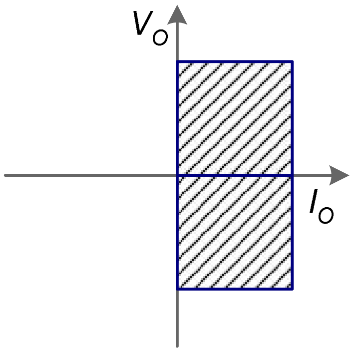


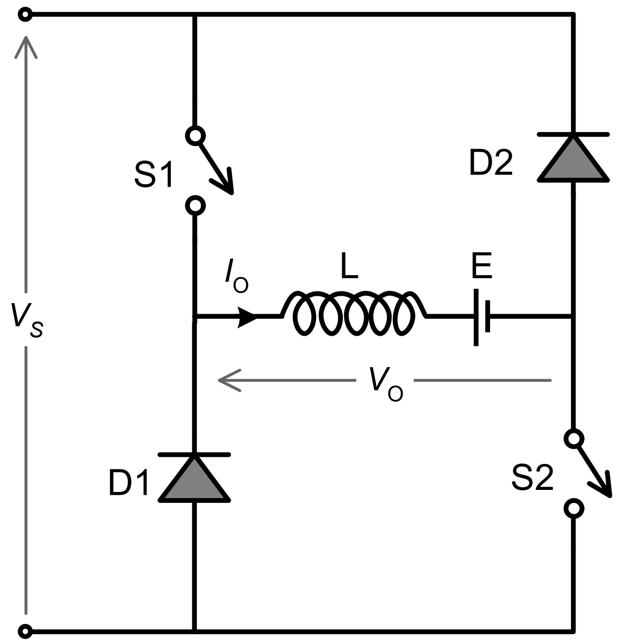


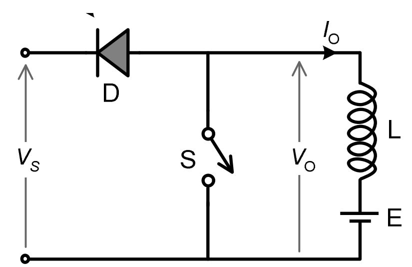


- Depending on duty cycle, the average value of load current I_O may be either positive or negative

Type D Chopper

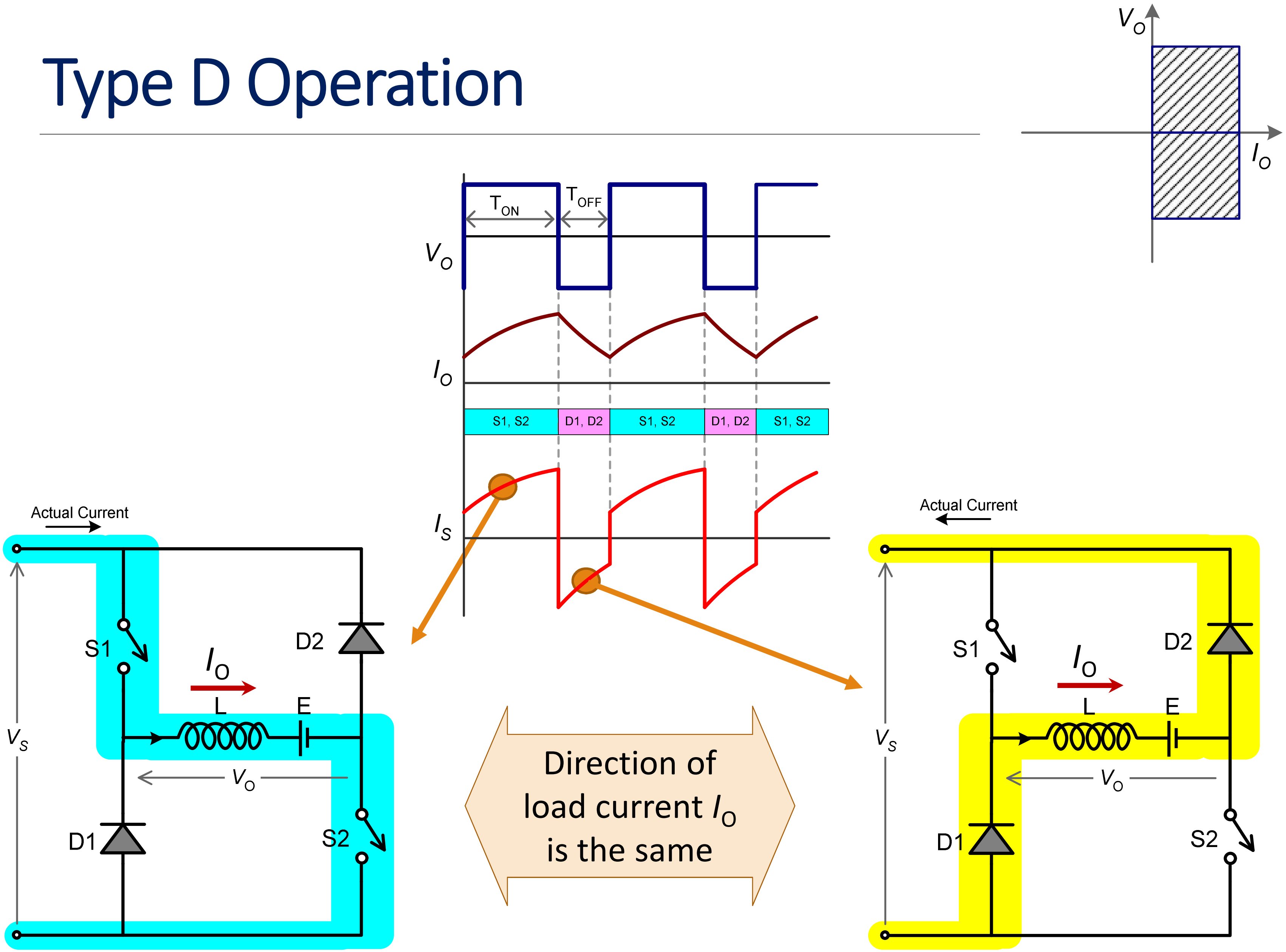






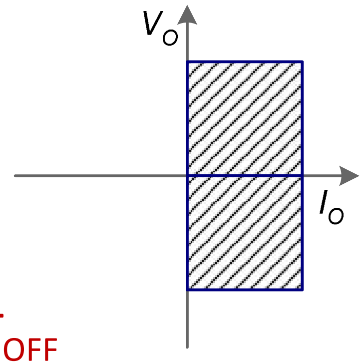
Is a combination of two Type B Choppers

Type D Operation

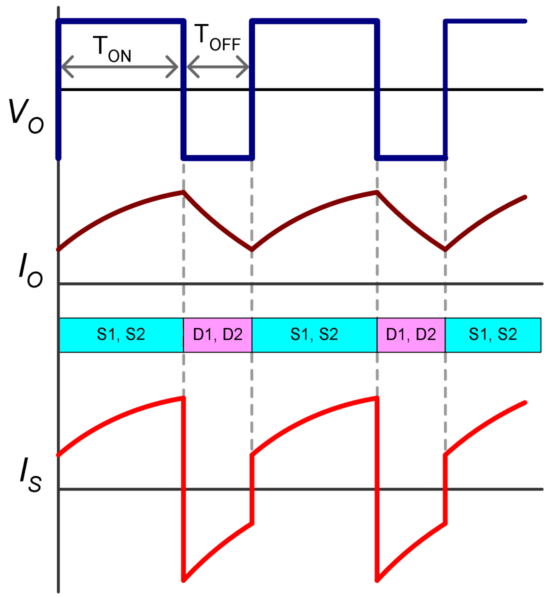


Direction of load current I_O is the same

Type D Waveforms

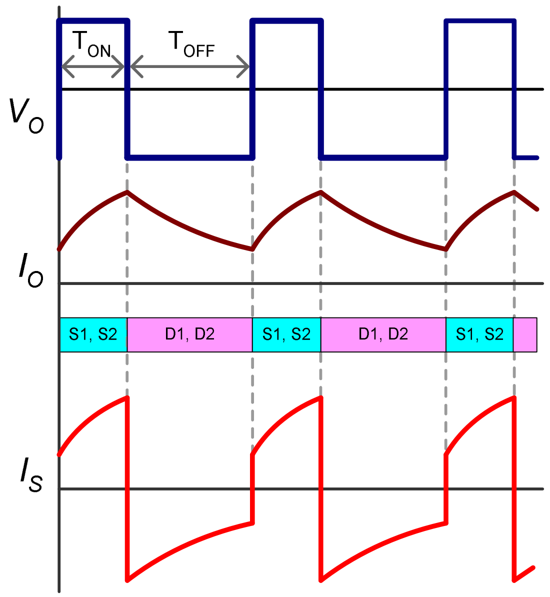


$T_{ON} > T_{OFF}$



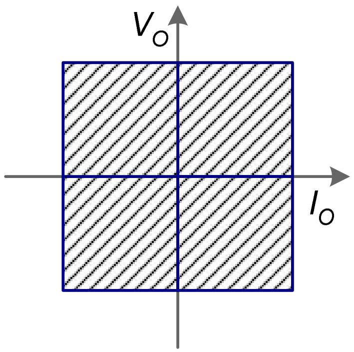
Average voltage is positive and output current is also positive; so first quadrant operation

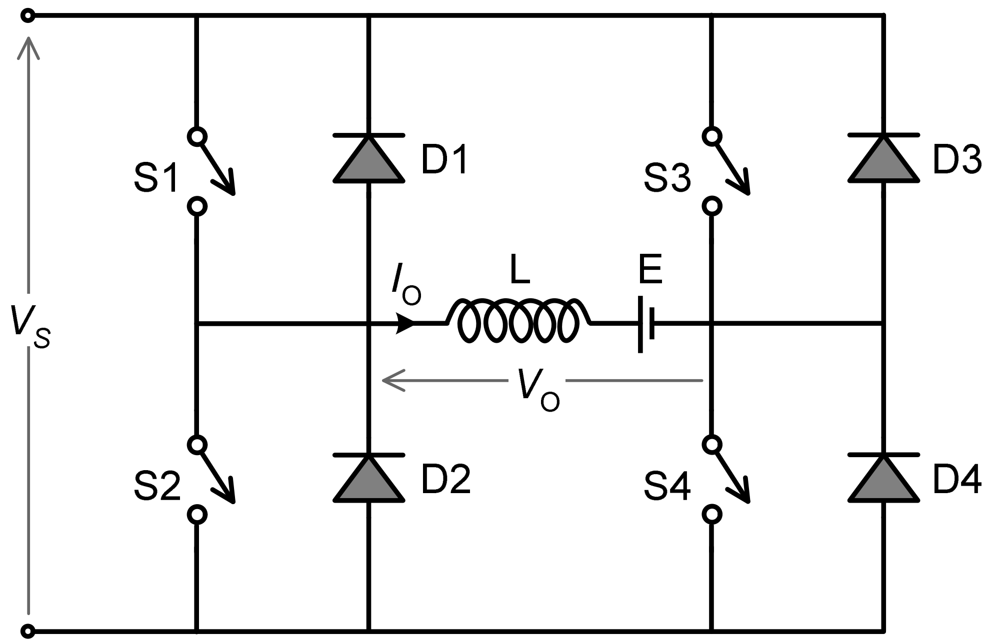
$T_{ON} < T_{OFF}$

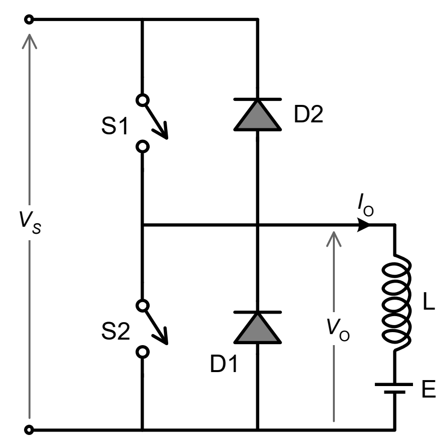


Average voltage is negative and output current is positive; so fourth quadrant operation

Type E Chopper

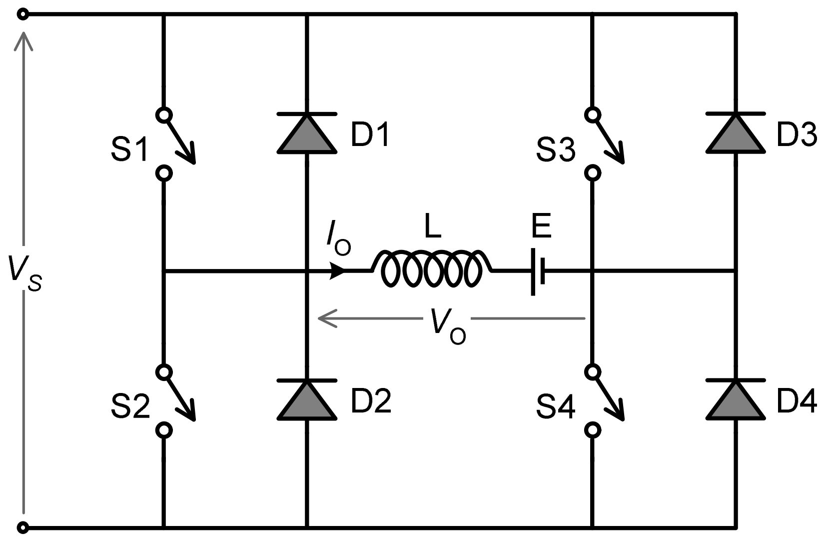


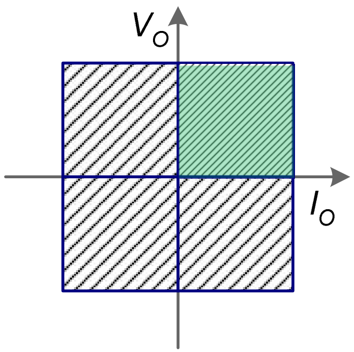




Is a combination of two Type C Choppers

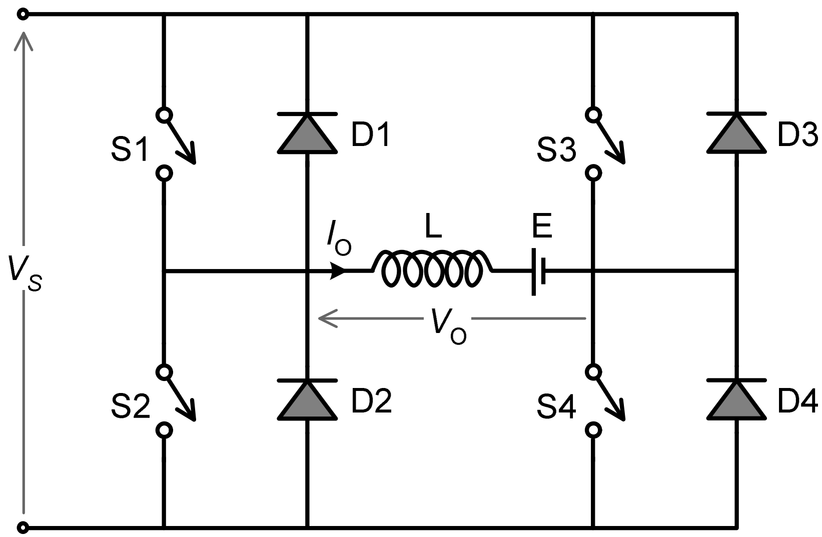
Type E Chopper – in Q1

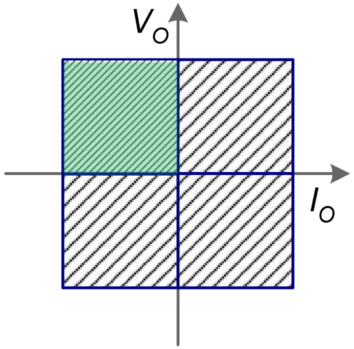




First Quadrant Operation			
Common Condition	**Operation**	**Current flow**	**Action**
S2, S3 off, S4 is kept on	S1 is turned on	through S1, L, E and S4	Energy stored in Inductor L
	S1 is turned off	through D2, L, E and S4	Freewheeling current flows

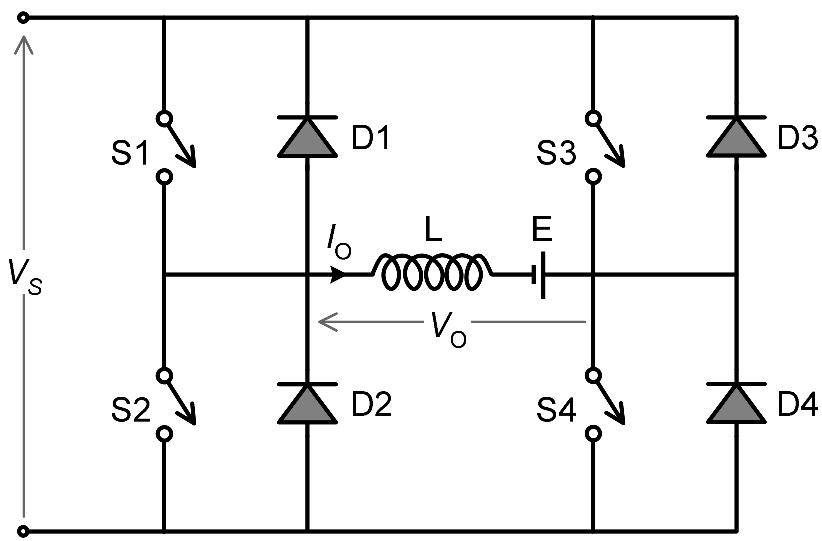
Type E Chopper – in Q2

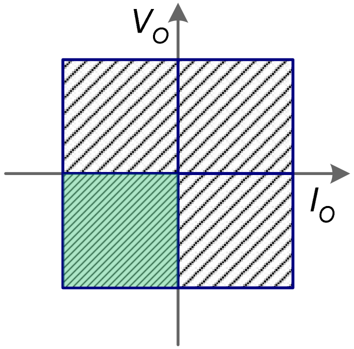




Second Quadrant Operation			
Common Condition	**Operation**	**Current flow**	**Action**
S1, S3 and S4 are kept off	S2 is turned on	through L, S2, D4 and E	Energy stored in Inductor L
	S2 is turned off	through D1, L, E and D4	Current fed back to source

Type E Chopper – in Q3

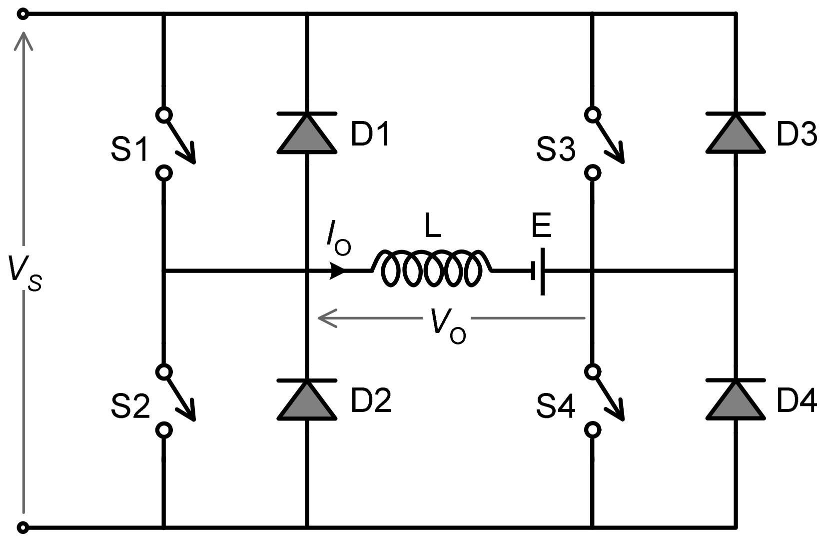


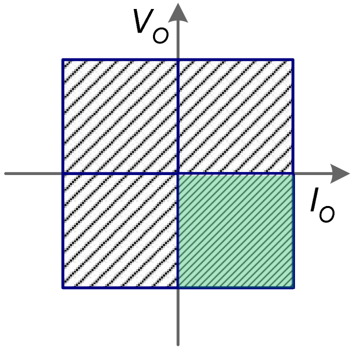


Polarity of E is reversed here

Third Quadrant Operation			
Common Condition	**Operation**	**Current flow**	**Action**
S1, S4 off, S2 is kept on	S3 is turned on	through S3, E, L and S2	Energy stored in Inductor L
	S3 is turned off	through L, S2, D4 and E	Freewheeling current flows

Type E Chopper – in Q4





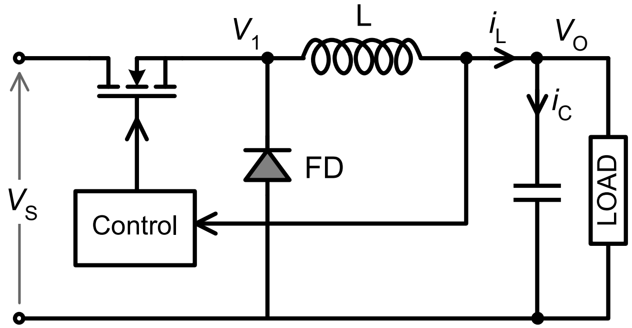
Polarity of E is reversed here

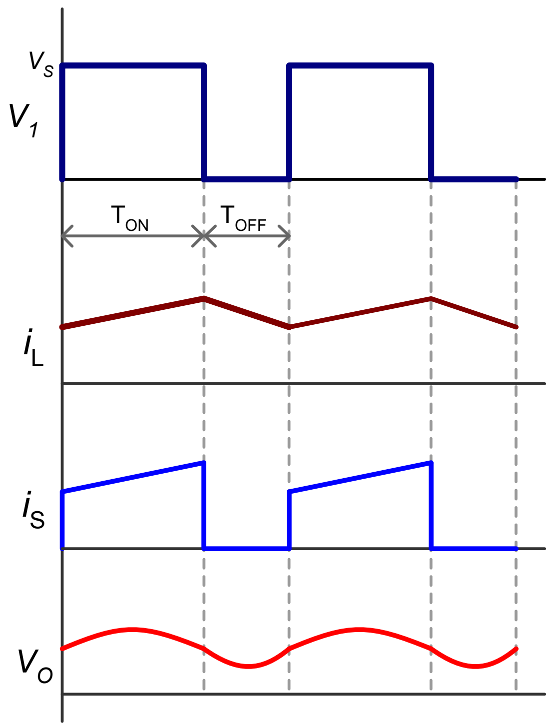
Fourth Quadrant Operation			
Common Condition	**Operation**	**Current flow**	**Action**
S1, S2 and S3 are kept off	S4 is turned on	through S4, D2, L and E	Energy stored in Inductor L
	S4 is turned off	through D3, E, L and D2	Current fed back to source

Switching Regulators

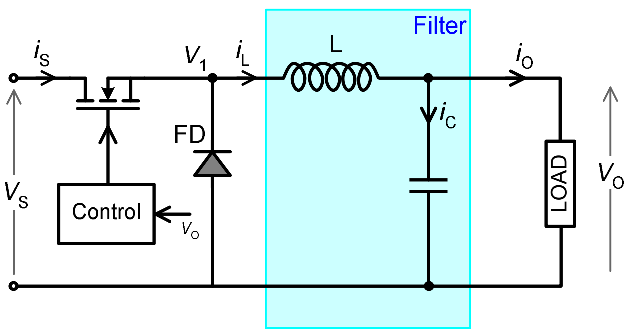
- Switching regulators are used to convert an unregulated DC voltage to regulated DC voltage
- Buck, Boost and Buck-boost type are available
- Efficient compared to linear regulators

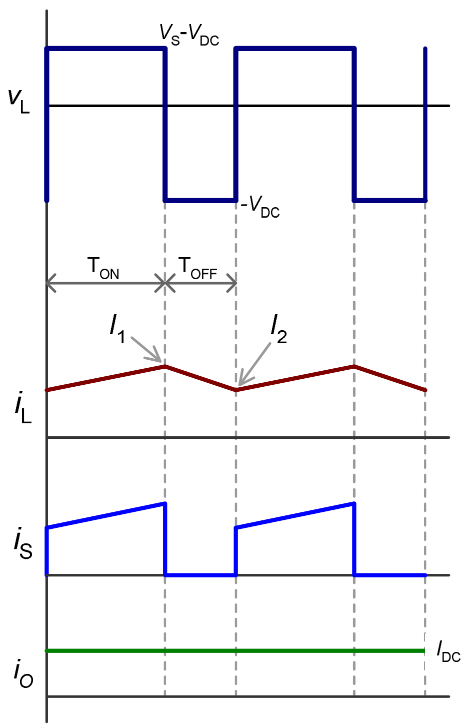
Buck type regulator





Filter Design





Voltage across inductor, $v_L = L\dfrac{di}{dt}$

During rise time of i_L

$$V_S - V_{DC} = L\frac{I_2 - I_1}{T_{ON}} = L\frac{\Delta I}{T_{ON}} \qquad T_{ON} = \frac{L\,\Delta I}{V_S - V_{DC}}$$

During fall time of i_L

$$-V_{DC} = L\frac{I_1 - I_2}{T_{OFF}} = L\frac{\Delta I}{T_{OFF}} \qquad T_{OFF} = \frac{L\,\Delta I}{V_{DC}}$$

Equating ΔI from the two expressions

$$T = T_{ON} + T_{OFF}$$

$$\Delta I = \frac{\left(V_S - V_{DC}\right)T_{ON}}{L} = \frac{V_{DC}\,T_{OFF}}{L}$$

If α is duty cycle $\qquad T_{ON} = \alpha T \qquad T_{OFF} = \left(1-\alpha\right)T$

$$\alpha = \frac{T_{ON}}{T_{ON} + T_{OFF}} \qquad V_{DC} = \alpha V_S \qquad \alpha = \frac{V_{DC}}{V_S}$$

$$T_{ON} = \frac{L\,\Delta I}{V_S - V_{DC}} \qquad T_{OFF} = \frac{L\,\Delta I}{V_{DC}}$$

$$T = \frac{1}{f} = T_{ON} + T_{OFF}$$

$$= \frac{L\,\Delta I}{V_S - V_{DC}} + \frac{L\,\Delta I}{V_{DC}} = \frac{V_{DC} L\,\Delta I + \left(V_S - V_{DC}\right) L\,\Delta I}{V_{DC}\left(V_S - V_{DC}\right)} = \frac{V_S\,L\,\Delta I}{V_{DC}\left(V_S - V_{DC}\right)}$$

$$ie. \quad \frac{1}{f} = \frac{V_S\,L\,\Delta I}{V_{DC}\left(V_S - V_{DC}\right)}$$

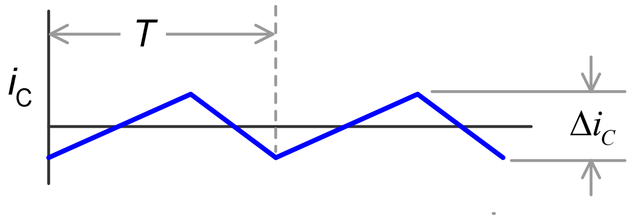
$$\Delta I = \frac{V_{DC}\left(V_S - V_{DC}\right)}{V_S\,f\,L} = \frac{\alpha V_S\left(V_S - \alpha V_S\right)}{V_S\,f\,L} = \frac{V_S \alpha\left(1-\alpha\right)}{f\,L}$$

$$\Delta I = \frac{V_S \alpha\left(1-\alpha\right)}{f\,L}$$

Applying KCL $\quad i_L = i_C + i_O$

If load ripple current is assumed to be zero $\quad \Delta i_L = \Delta i_C$

Average capacitor current for a duration $\frac{T}{2}$, $I_C = \frac{\Delta I}{4}$



Peak-to-peak ripple voltage of capacitor, $\Delta v_C = \frac{1}{C}\int_0^{T/2} \frac{\Delta I}{4}\,dt = \frac{\Delta I\,T}{8C} = \frac{\Delta I}{8\,C\,f}$

$$\Delta I = \frac{V_S\alpha(1-\alpha)}{f\,L}$$

Substituting the value of *ΔI*

$$\Delta v_C = \frac{V_S\alpha(1-\alpha)}{8\,f^2 LC}$$

Example

A buck regulator has an input voltage of 120V, and the average output voltage is 70V. Average load current is 25A and the switching frequency of 25 kHz. The peak to peak ripple current in inductor is limited to 1A and the peak-to-peak ripple voltage at the output is 2V. Find the value of inductor and capacitor.

Applicable equations:

$$\Delta I = \frac{V_S \alpha \left(1-\alpha\right)}{f\ L}$$

$$\Delta v_C = \frac{V_S \alpha (1-\alpha)}{8\ f^2 LC}$$

Solution

$$\text{Duty cycle, } \alpha = \frac{V_{DC}}{V_S} = \frac{70}{120} = 0.5833$$

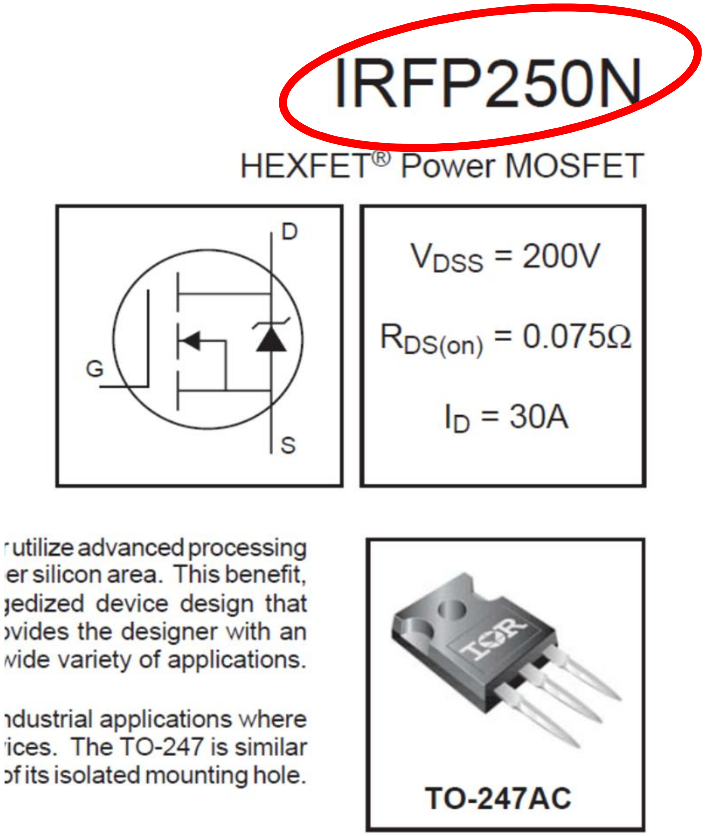
$$\Delta I = \frac{V_S \alpha \left(1-\alpha\right)}{f\ L}$$

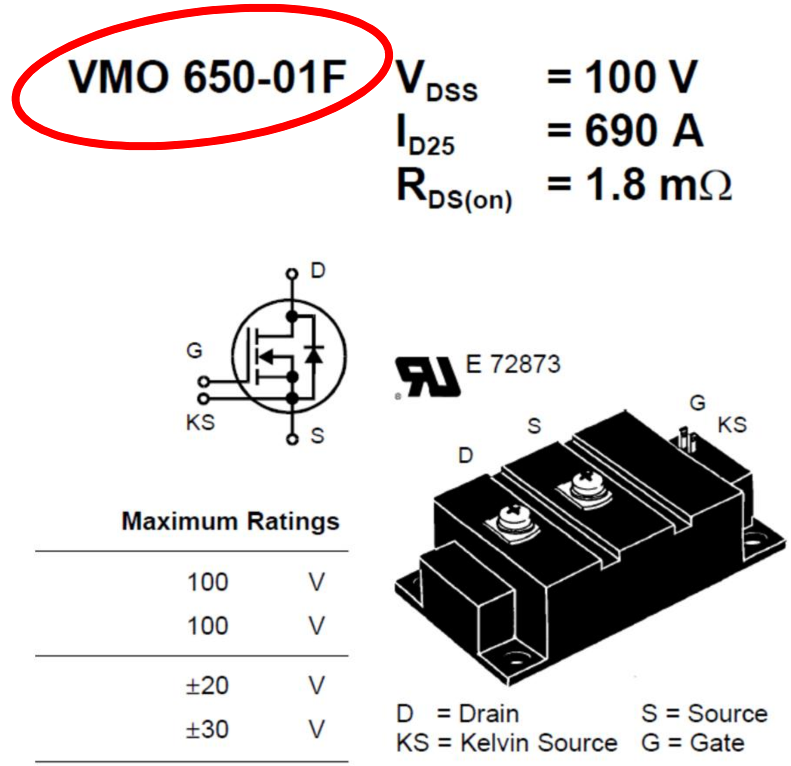
$$1.0 = \frac{120 \times 0.5833\left(1-0.5833\right)}{25 \times 10^3 \times L} \qquad L = 1.17 \text{ mH}$$

$$\Delta v_C = \frac{V_S \alpha (1-\alpha)}{8\ f^2 LC}$$

$$2.0 = \frac{120 \times 0.5833(1-0.5833)}{8\left(25 \times 10^3\right)^2 \times 1.17 \times 10^{-3} \times C} \qquad C = 2.49\ \mu\text{F}$$

Typical MOSFETS





Typical IGBTs