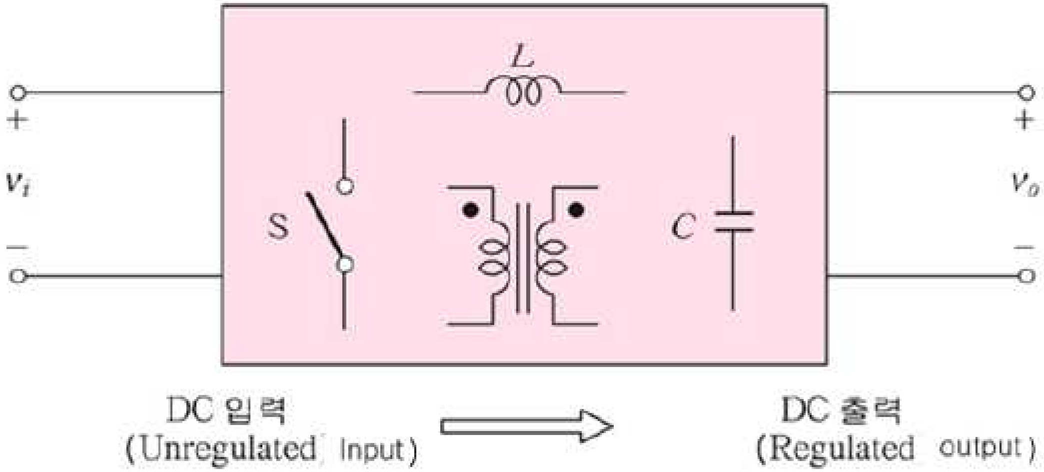
5. DC-DC 컨버터

제 5 장 DC-DC 컨버터

- 전력변환의 기본원리
- Buck 컨버터
- Boost 컨버터
- Buck-Boost 컨버터
- Forward 컨버터
- Flyback 컨버터

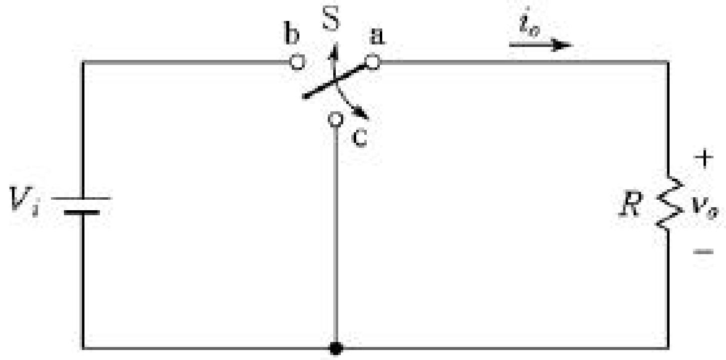
DC-DC 컨버터의 개념도

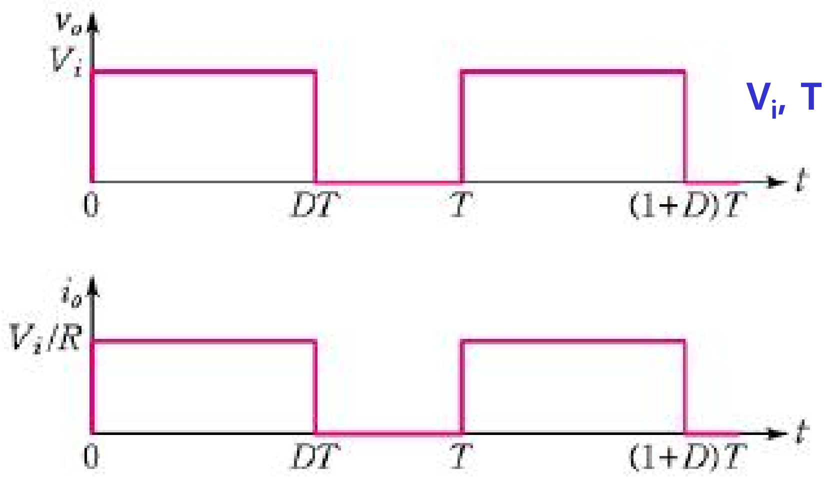


DC-DC 컨버터의 개념도

Unregulated dc 입력 → regulated dc 출력
Configuration:
1. Switch (MOSFET, IGBT, Diode) : Energy flow control
2. 인덕터, 커패시터 : 에너지 전달 매개체, Low pass filter (ripple 감소)
3. 변압기 : 전압이득 조절, 전기적인 isolation
4. 제어기 설계

간략한 형태의 DC-DC 컨버터





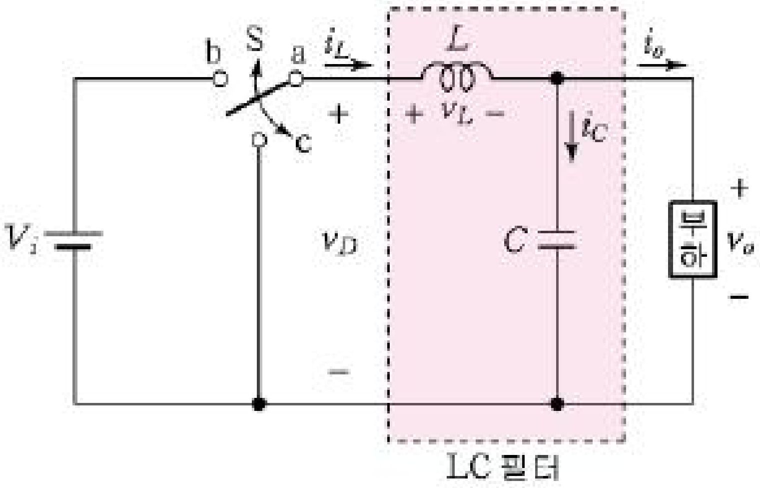
V_i, T 일정

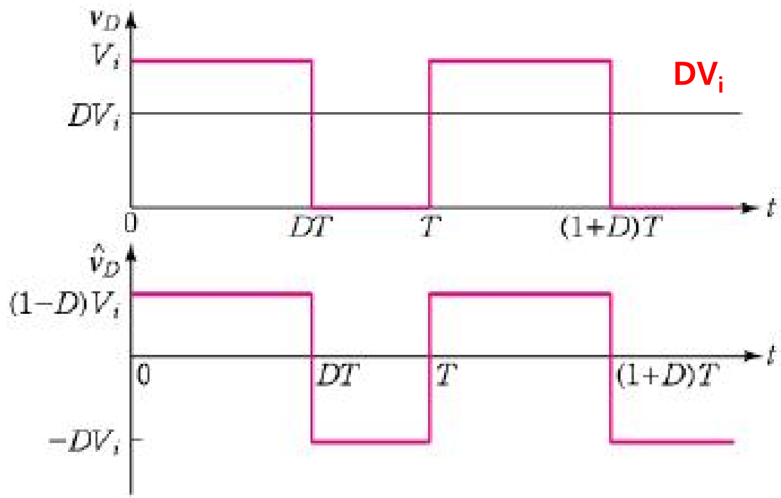
D (duty ratio, 통류율) : 0 ~ 1 범위, 스위치 on 구간
0 ~ DT : switch ab → v_o = V_i, 전력전달구간
DT ~ T : switch ac → v_o = 0, 입력/ 출력 분리
< v_o>, <p_o> 는 D에 비례

$$V_0 = \frac{1}{T} \cdot [\, DT \cdot V_i + (1-D)T \cdot 0 \,] = DV_i$$

$$P_0 = \frac{1}{T} \cdot [\, DT \cdot \frac{V_i^2}{R} + (1-D)T \cdot 0 \,] = D\frac{V_i^2}{R}$$

Buck 컨버터 기본회로와 파형





$$v_D = v_{DC} + v_{AC} \qquad v_{DC} = DV_i$$

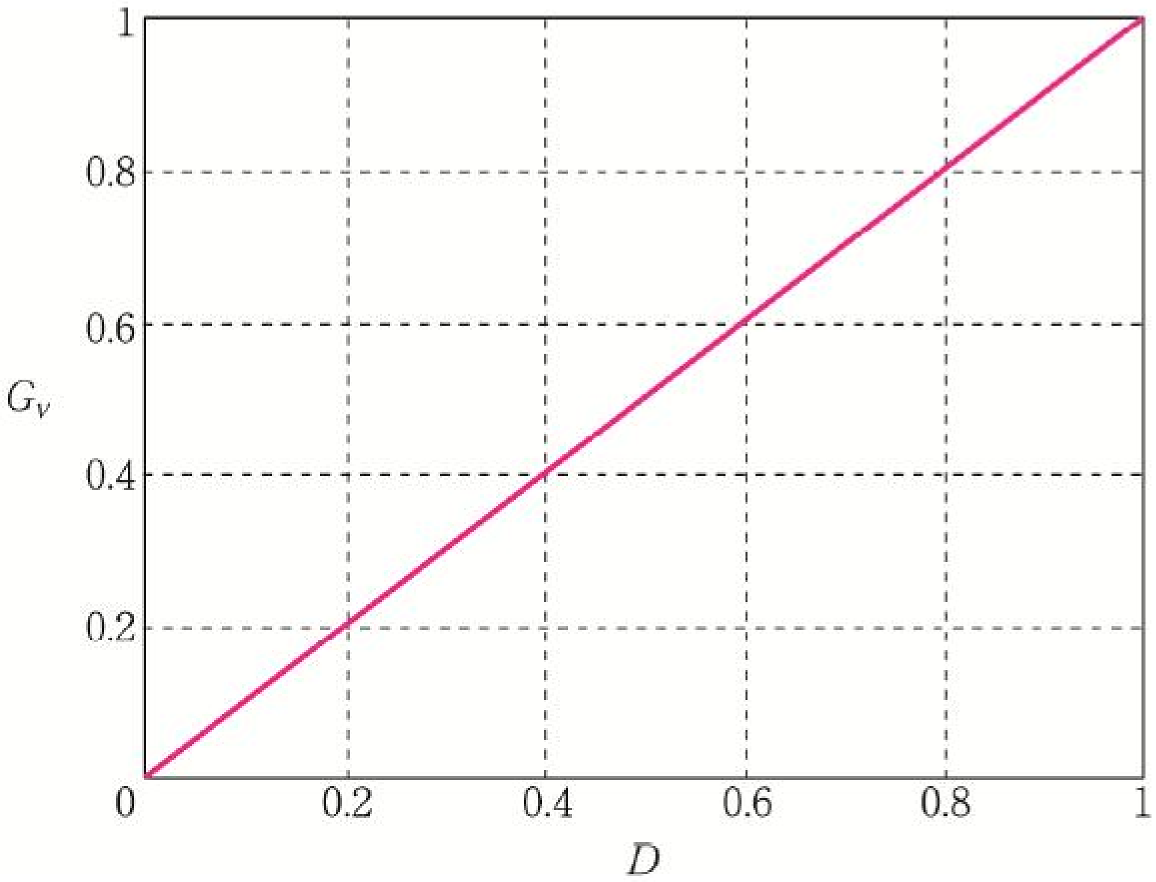
$$v_{AC} = v_D - v_{DC} = v_D - DV_i$$

$$G_V \equiv \frac{V_0}{V_i} = \frac{DV_i}{V_i} = D$$

출력전압 : DC+AC 성분
LC low pass filter : 교류성분 차단, regulate 된 직류전압 생성

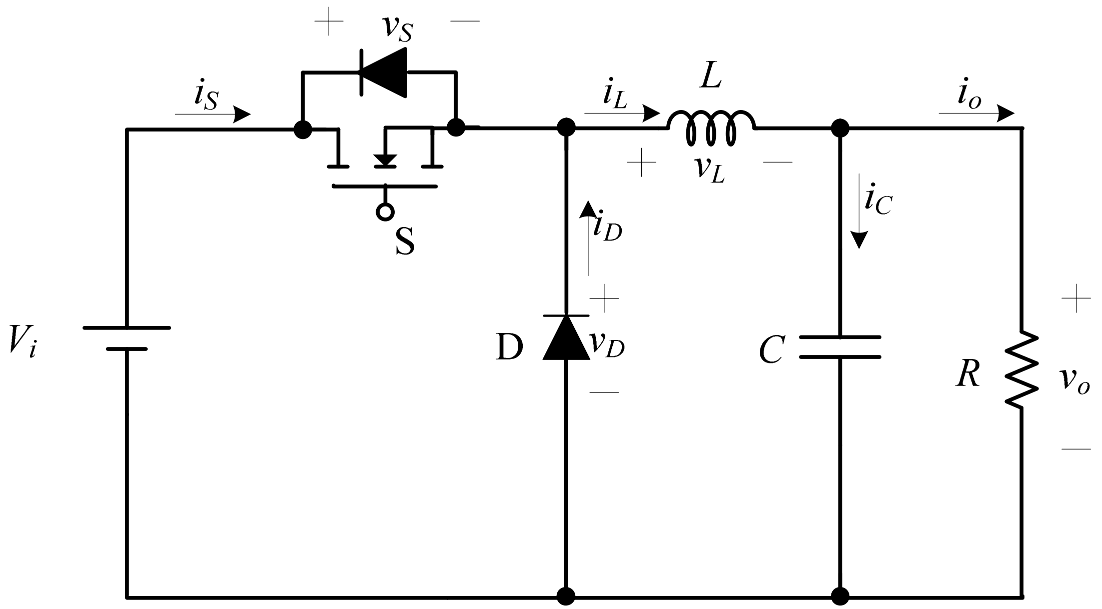
출력전압 v_o < 입력전압 V_i → 강압형 (Step down)

통류율(Duty Ratio)과 전압전달비



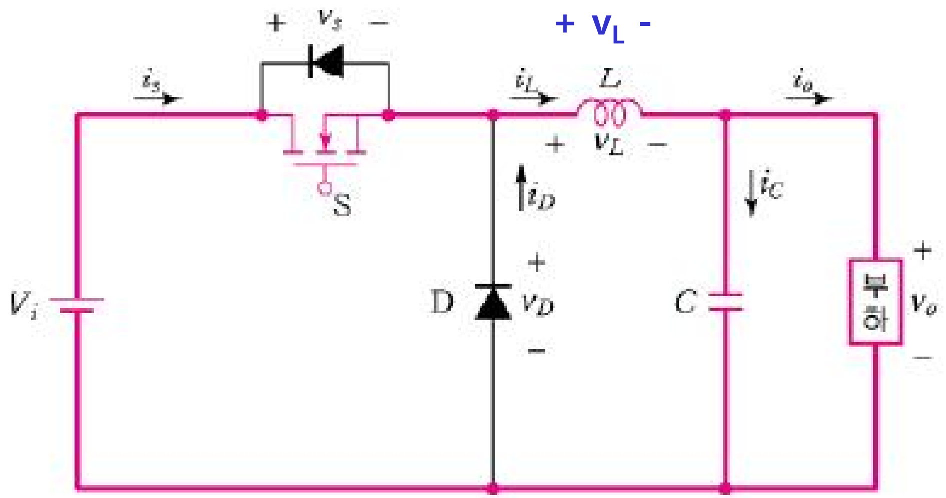
$$G_V \equiv \frac{V_0}{V_i} = \frac{DV_i}{V_i} = D$$

Buck 컨버터의 실제적인 구성



MOSFET S : on-off 제어로 입력전원의 에너지를 출력으로 전달 (active switch)
Diode D : MOSFET가 off 되는 구간 동안 인덕터 전류 i_L이 흐를수 있도록 path 제공
→ freewheeling path (passive switch)
$0 < t < DT$: S on, $v_D = V_i$ → reverse bias → off
$DT < t < T$: S off, $v_D = 0$ → forward bias → on

DT 구간 : 스위치 on

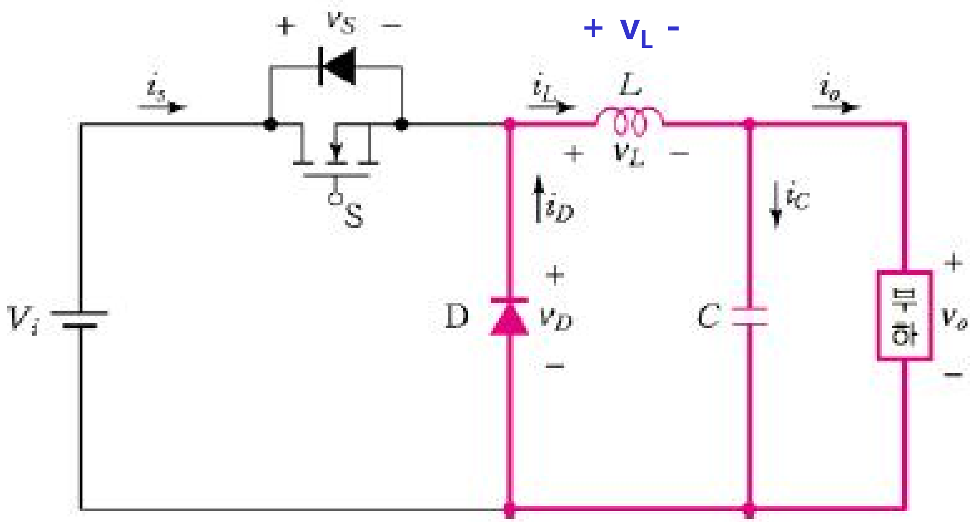


S on : $v_S = 0$, $i_S = i_L$
D off : $v_D = V_i$, $i_D = 0$
$v_L = V_i - V_O > 0$ $(V_i > V_o)$
→ i_L 증가 (상승)
$P_L = v_L i_L > 0$
$E_L = ½L i_L^2$ → 증가

$0 < t < DT$ (MOSFET S on, Diode D off)

$< v_o > < V_i$
정상상태 : 한 주기의 시작과 끝에서 i_L, v_o의 값이 같다.
- 인덕터 전류 i_L, 커패시터 전압 v_o = 출력전압
L & C are finite

(1-D)T 구간 : Diode on

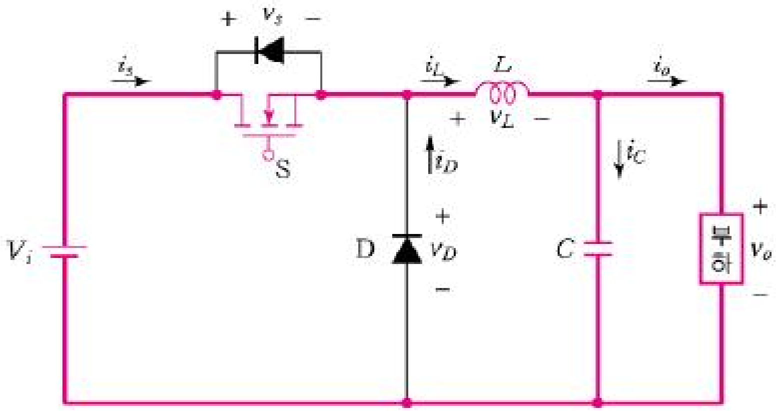


+ v_L -

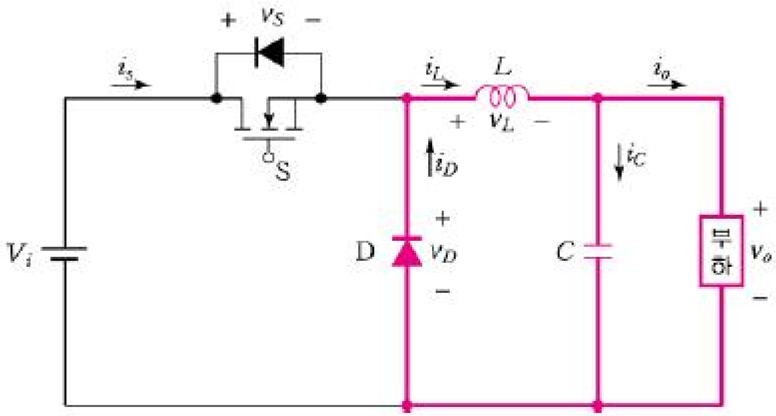
S off : $v_S = V_i$, $i_S = 0$
D on : $v_D = 0$, $i_D = i_L$
$v_L = -V_O < 0$
→ i_L 감소 (하강)
$P_L = v_L i_L < 0$
$E_L = ½L i_L^2$ → 감소

DT < t < T (MOSFET S off, Diode D on)

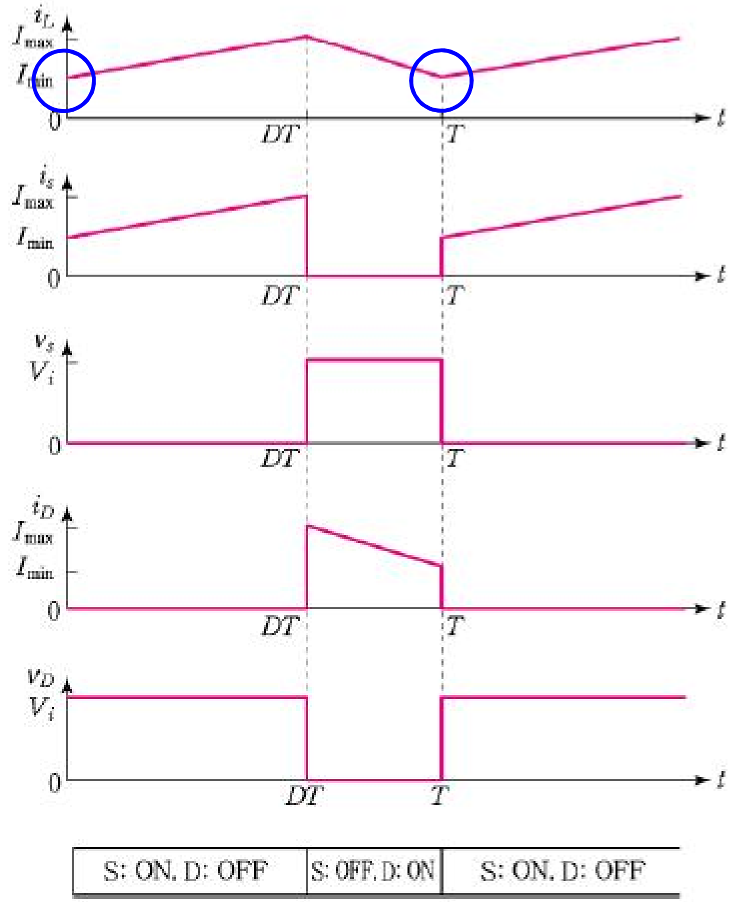
Buck 컨버터 회로 각부의 파형



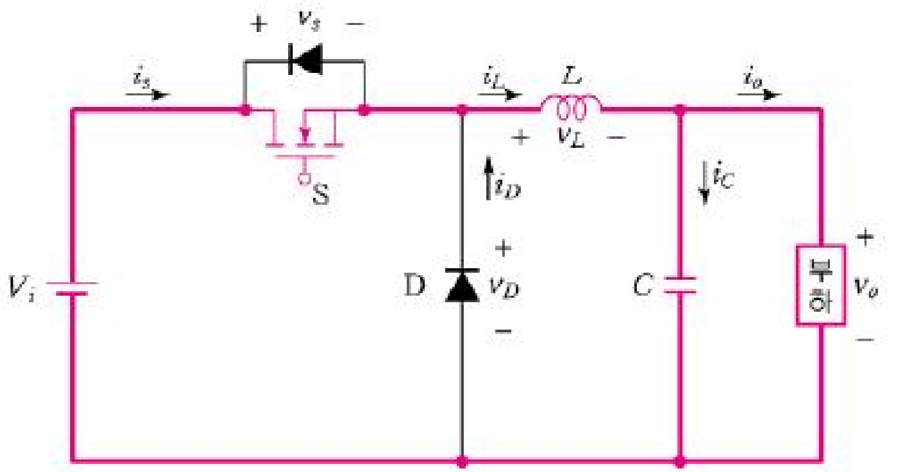
0 < t < DT (MOSFET S on, Diode D off)

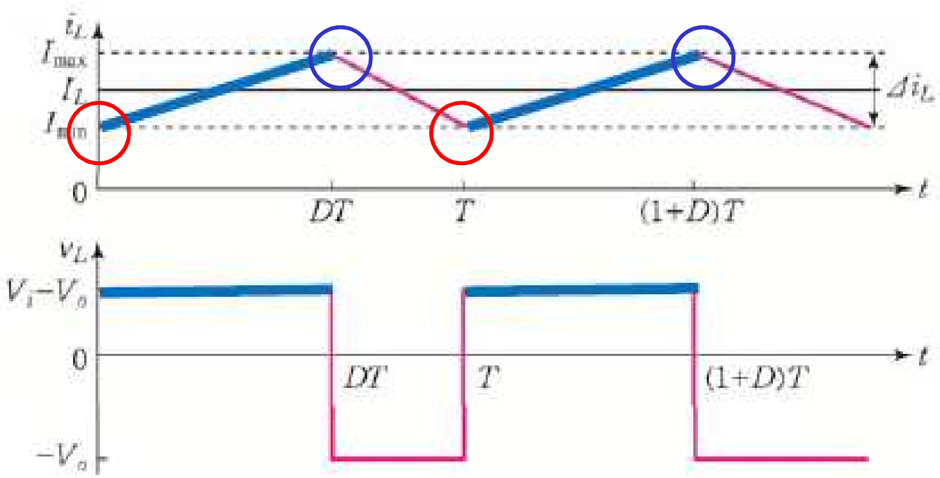


DT < t < T (MOSFET S off, Diode D on)



인덕터 전류 : 전류상승구간 (0 < t < DT)





i) $0 \le t < DT$

$$v_L = V_i - V_0$$

$$v_L = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_i - V_0}{L} \qquad i_L(t) = \frac{1}{L}\int_0^t (V_i - V_0)\,dt + I_{min}$$

DT 구간 동안 인덕터 전류의 상승폭 Δi_L

$$\Delta i_L = \frac{V_i - V_0}{L}\cdot DT$$

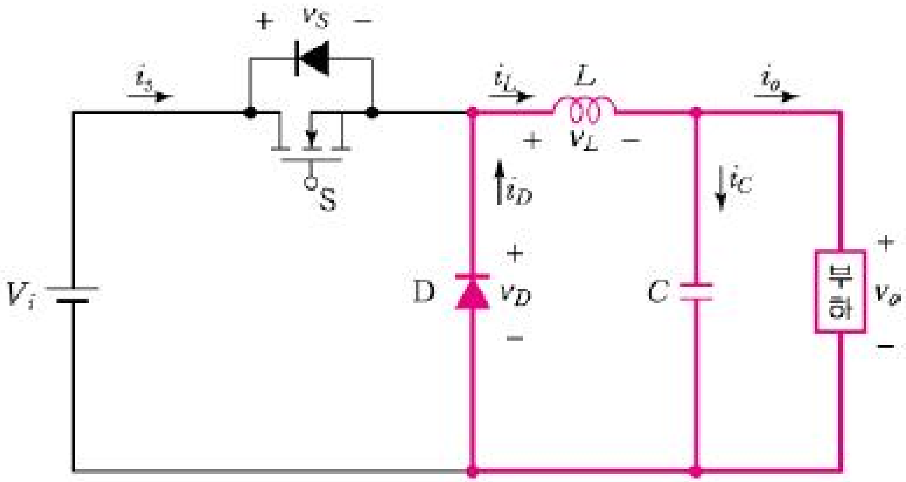
$$I_{max} = I_L + \frac{1}{2}\Delta i_L = I_o + \frac{V_i - V_0}{2L}\cdot DT$$

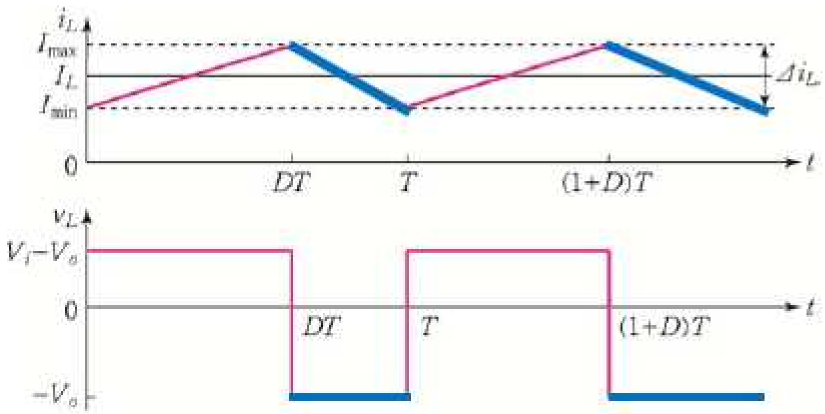
$$= I_o + \frac{V_i}{2L}\cdot(1-D)\cdot DT$$

$$I_{min} = I_L - \frac{1}{2}\Delta i_L = I_o - \frac{V_i - V_0}{2L}\cdot DT$$

$$= I_o - \frac{V_i}{2L}\cdot(1-D)\cdot DT$$

인덕터 전류 : 전류하강구간 (DT < t < T)





ii) $DT \le t < T$

$$v_L = -v_0$$

$$\frac{di_L}{dt} = -\frac{v_0}{L} \qquad i_L(t) = \frac{1}{L}\int_{DT}^{t}(-V_0)\,dt + I_{max}$$

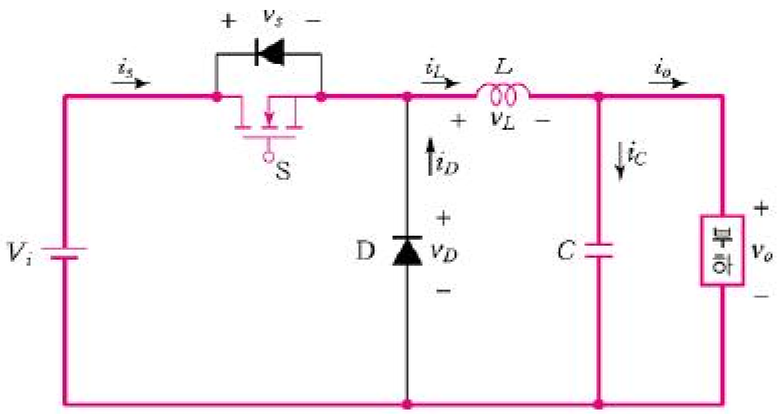
(1-D)T 구간 동안 인덕터 전류의 하강폭 Δi_L

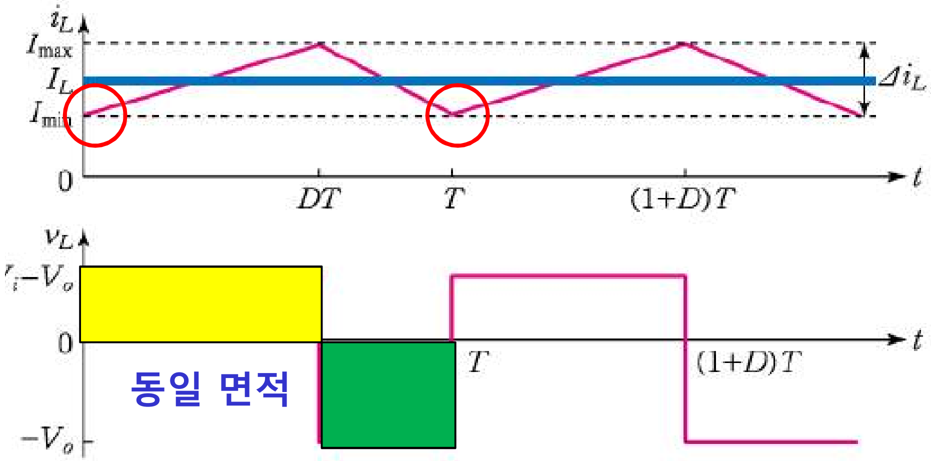
$$\Delta i_L = \frac{V_0}{L}\cdot(1-D)T$$

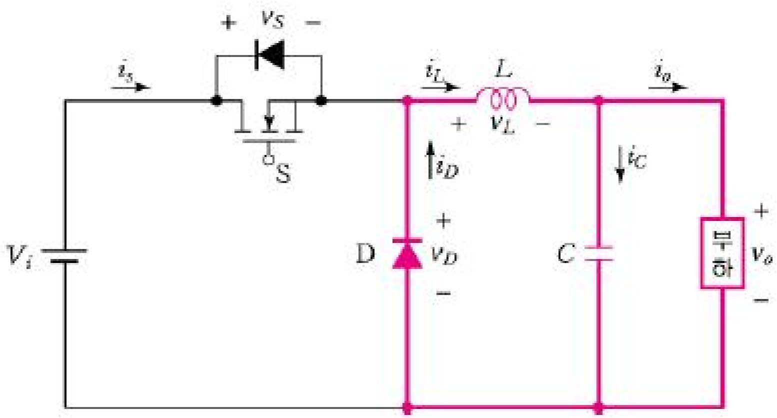
$$I_{max} = I_L + \frac{1}{2}\Delta i_L = I_o + \frac{V_0}{2L}\cdot(1-D)T$$

$$I_{min} = I_L - \frac{1}{2}\Delta i_L = I_o - \frac{V_0}{2L}\cdot(1-D)T$$

인덕터 전압파형







정상상태에서 상승폭Δi_L=하강폭 Δi_L

$$\frac{V_i - V_o}{L} DT = \frac{V_o}{L}(1-D)T$$

$$(V_i - V_o)DT = V_o(1-D)T$$

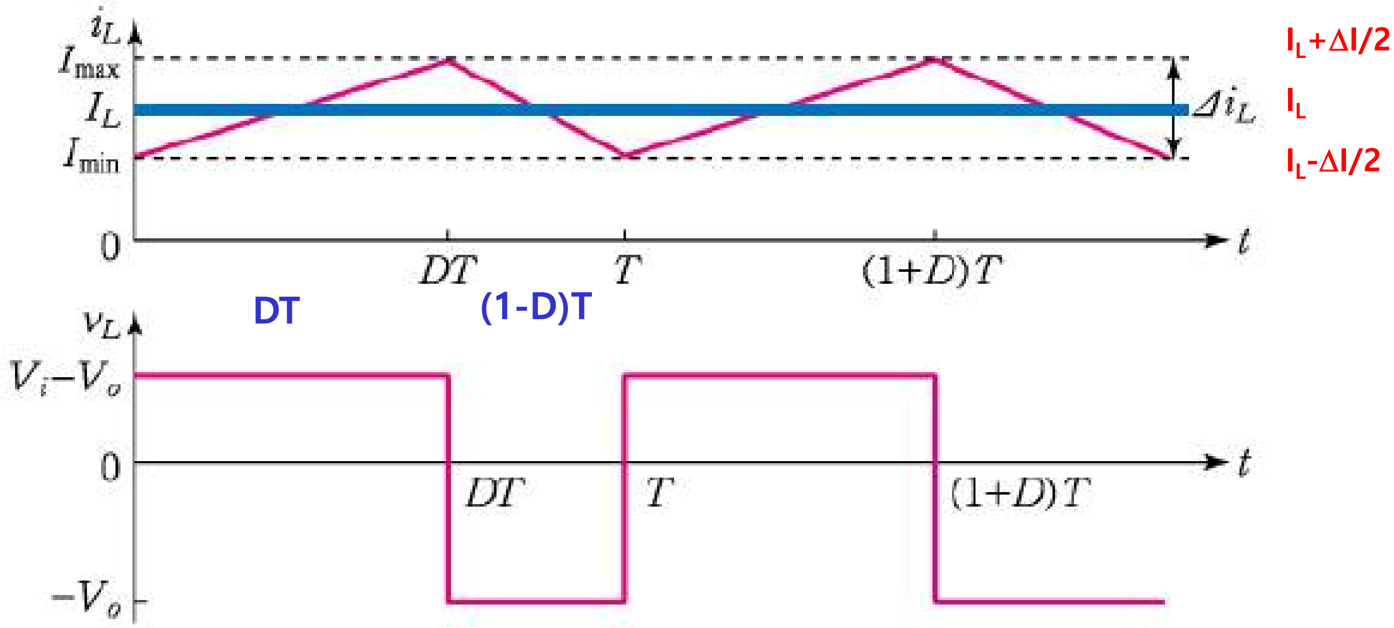
$$V_o = DV_i$$

인덕터 전압 x 시간은 DT와 (1-D)T 구간에서 동일

$$(V_i - V_o) \cdot DT = V_o \cdot (1-D)T$$

$$V_o = DV_i$$

인덕터 평균전류 i_L



$i_L = i_C + i_o$ 정상상태에서 커패시터 전류의 평균값 I_C = 0이므로

$$I_L = I_o$$

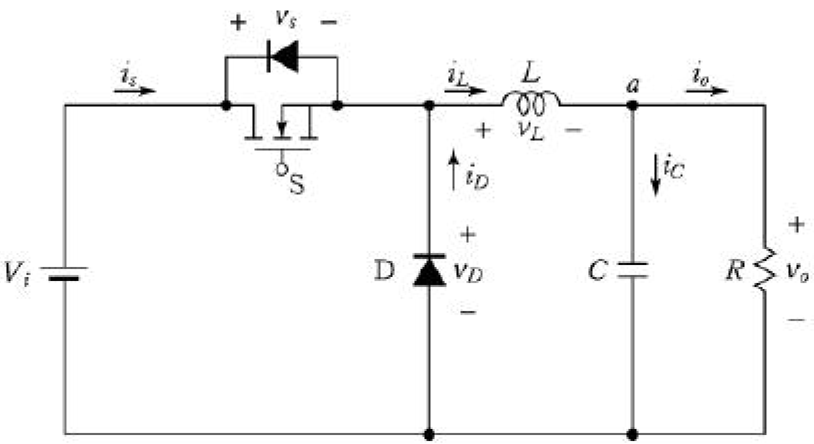
$i_L = I_L$ (직류성분) + $\hat{i}_L$ (교류성분)

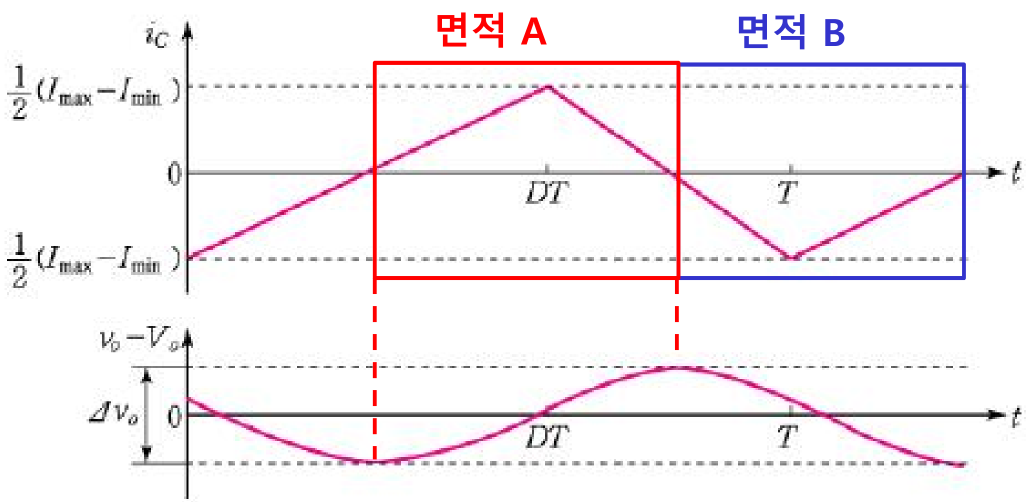
인덕터 전류 : v_L/L의 기울기로

DT (S on, D off) 구간 동안 선형적으로 증가

(1-D)T (S off, D on) 구간 동안 선형적으로 감소

출력 전압 v_o





$$I_0 = \frac{V_0}{R}$$

$$i_C = i_L - I_o = C\frac{dv_o}{dt}$$

$$\Delta v_0 = \frac{1}{C}\left[\frac{1}{2}\left(\frac{I_{max} - I_{min}}{2}\right) \bullet \frac{T}{2}\right]$$

면적 A

$$= \frac{1}{C}\left(I_{max} - I_{min}\right) \bullet \frac{T}{8}$$

$$I_{max} - I_{min} = \frac{V_i - DV_i}{L} DT$$

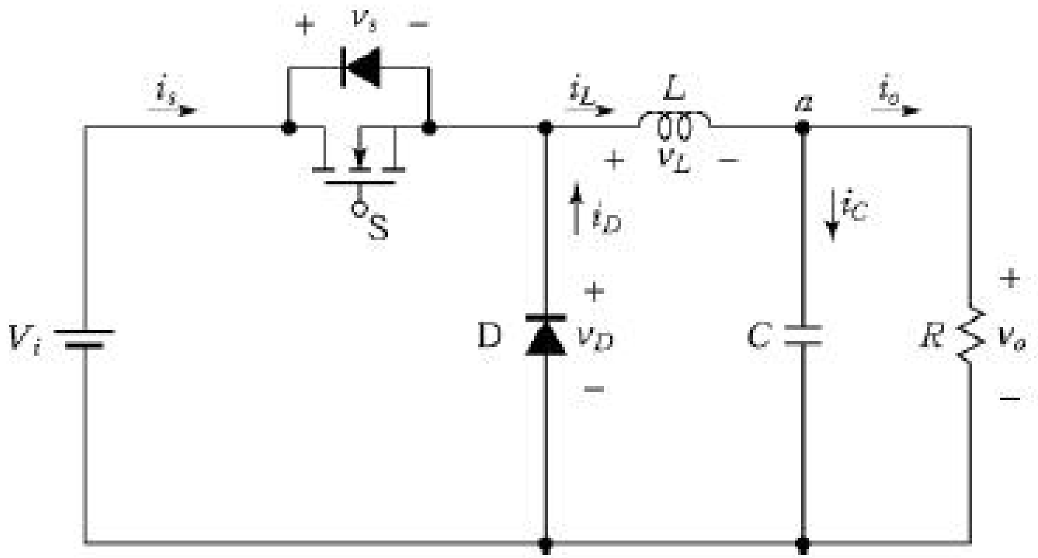
$$\Delta v_0 = \frac{1}{LC} \frac{V_i(1-D)D \bullet T^2}{8}$$

예제 5-2

<예제 5 – 2>

$V_i = 100,\ f_s = 100KH,\ D = 0.6,\ R = 10,\ L = 50\mu H,\ C = 100\mu F$

(a) V_0, I_0 (b) $I_{\max}, I_{\min}$ (c) Δv_0



DC transformer

$P_{in} = V_i I_S$

$P_o = V_o I_o = V_o I_L$

$P_{in} = P_o \quad V_o = DV_i$

$I_S = \dfrac{V_o}{V_i} I_o = DI_o$

예제 5-2

입력전압 100V, 100 kHz, D=0.6, R =10 ohm, L = 10 uH, C=100 uF

<풀이>

$$V_0 = DV_i = 0.6 \times 100 = 60 \ldots V$$

$$I_L = I_0 = \frac{V_0}{R} = \frac{60}{10} = 6 \quad A$$

$$I_{\max} = I_L + V_0 \bullet \frac{1-D}{2L} \bullet T$$

$$= 6 + 60 \times \frac{1-0.6}{2 \times 50 \times 10^{-6}} \times 10^{-5} \quad = 6 + 2.4 = 8.4 \quad A$$

$$I_{\max} = I_L - V_0 \bullet \frac{1-D}{2L} \bullet T$$

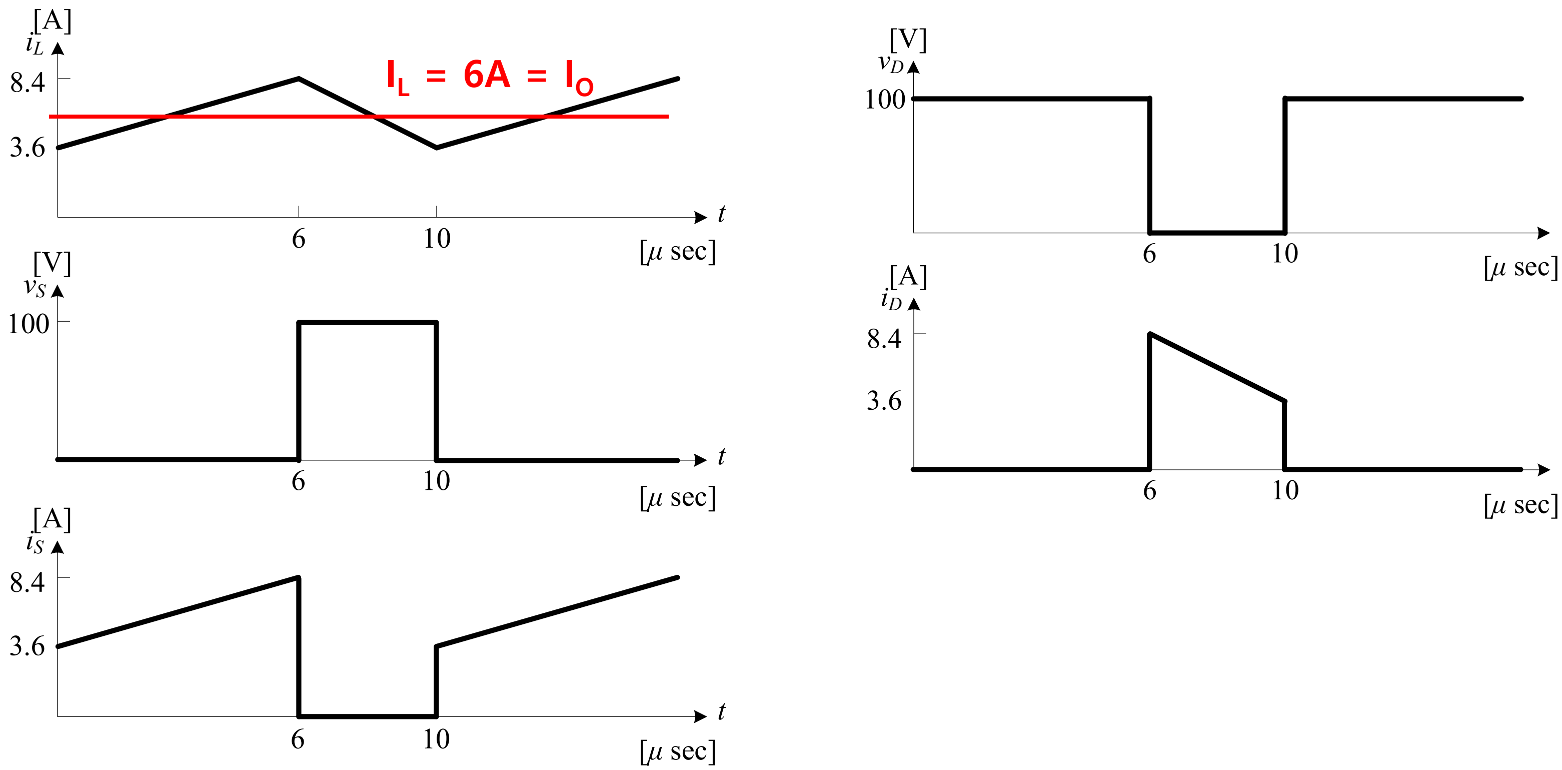
$$= 6 - 60 \times \frac{1-0.6}{2 \times 50 \times 10^{-6}} \times 10^{-5} \quad = 6 - 2.4 = 3.6 \quad A$$

$$\Delta v_0 = \frac{1}{LC} \frac{V_i (1-D) D \bullet T^2}{8}$$

$$= \frac{1}{100 \times 10^{-6}} \times (8.4 - 3.6) \times \frac{10^{-5}}{8} = \frac{4.8}{80} = 0.06 \quad V$$

예제 5-3

<예제5−3> 예제5−2에서 i_L, v_S, i_S, v_0, i_D 파형

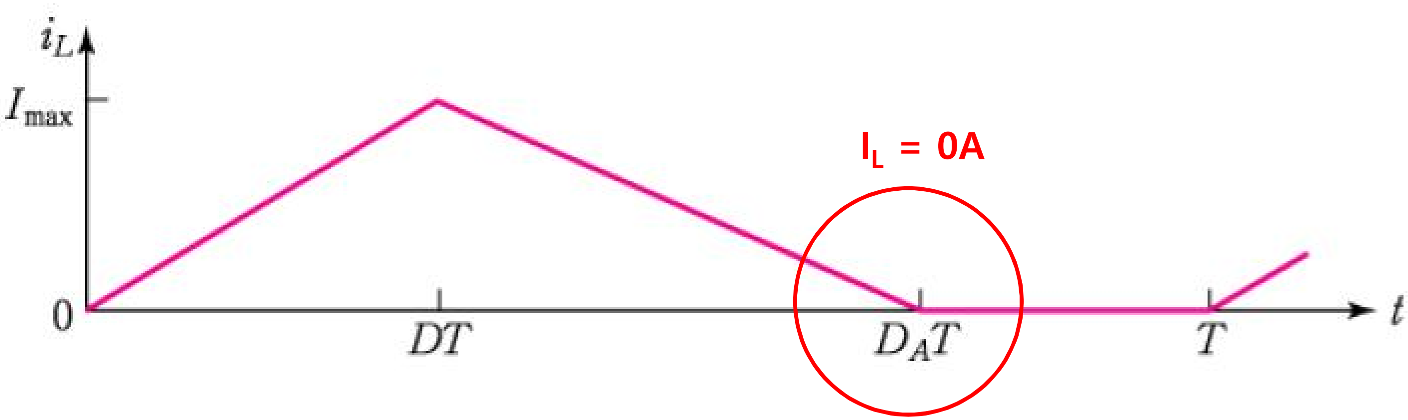


전류 불연속 모드

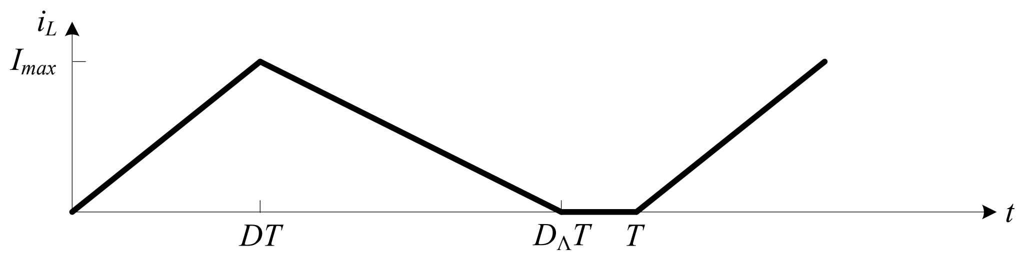
전류 불연속 모드 (Discontinuous mode) 조건

$$I_{\min} = I_L - V_o \frac{1-D}{2L} T = I_o - V_i \frac{D(1-D)}{2L} T < 0$$

1) 인덕터전류 i_L
   $I_{min} = 0$
   $D_A T < t < T$: $i_L = 0$ → switch S와 diode D가 동시에 off
2) 출력전압 v_o
   컨버터 입력에너지 E_{in} = 출력으로 유출되는 에너지 E_o



불연속 모드 정상상태 해석



(i) $0 \le t \le DT$

$$i = \frac{V_i - V_0}{L} \cdot t$$

$$I_{\max} = \frac{V_i - V_0}{L} \cdot DT$$

(ii) $DT \le t \le D_A T$

$$i = I_{\max} - \frac{V_0}{L}(t - DT)$$

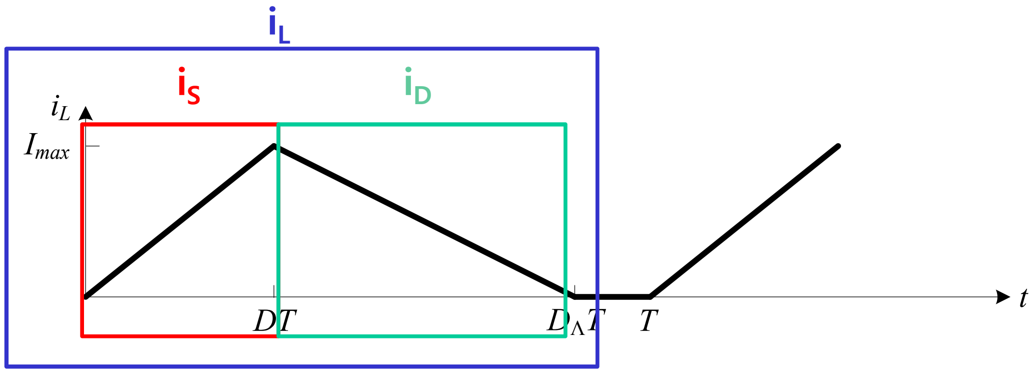
(iii) $D_A T \le t \le T$

$$i = 0$$

$0 = I_{\max} - \frac{V_0}{L}(D_A T - DT)$ 에서

$$D_A = D + \frac{L \cdot I_{\max}}{V_0 T}$$

불연속 모드 정상상태 해석



컨버터 입력 에너지 E_{in}= 출력에너지 E_0는 같으므로

$$E_{in} = V_i \cdot \boxed{\frac{I_{max}}{2} \cdot DT}$$

$$E_0 = V_0 \cdot \boxed{\frac{I_{max}}{2} \cdot D_A T}$$

$$\boxed{G_V \equiv \frac{V_0}{V_i} = \frac{D}{D_A}}$$

연속전류 : D_A = 1 → G_V=D
불연속전류 → 출력전압 증가

$$i_L(t = D_A T) = \frac{1}{L}\int_{DT}^{D_A T}(-V_0)\,dt + I_{max} = 0$$

$$I_{max} = \frac{V_o}{L}(D_A - A)\cdot T$$

$$D_A = D + \frac{LI_{max}}{TV_0}$$

출력전류 평균 I_O = 인덕터 전류 평균 I_L

$$I_L = I_O = \frac{I_{max}}{2}D_A \Rightarrow I_{max} = \frac{2I_O}{D_A}$$

$$D_A = D + \frac{2LI_0}{D_A TV_0} = D + \frac{2LI_0}{DTV_i}$$