DC-DC Converters

Mohammad Adnan
Program Studi S3 Ilmu Teknik Elektro
Universitas Hasanuddin
mohammad.adnan013@gmail.com

Abstract*—Dalam beberapa aplikasi, perlu untuk mengubah nilai tegangan DC konstan menjadi tegangan DC variabel. Dalam elektronika daya, rangkaian yang melakukan operasi ini disebut DC-DC converter. DC-DC converter juga dapat disebut sebagai pemotong DC. Konverter dapat dianggap sebagai rangkaian ekuivalen DC dari transformator dengan rasio belitan yang dapat disesuaikan secara kontinu. Karena transformator dapat menurunkan atau manaikkan tegangan AC, DC-DC converter juga dapat menurunkan atau manaikkan nilai tegangan sumber DC. DC-DC converter banyak digunakan di banyak peralatan kantor, catu daya komputer pribadi, sistem tenaga pesawat ruang angkasa, laptop, perangkat komunikasi, kontrol kecepatan dan pengereman di motor DC, palu tambang, lift barang, troli, dan mobil listrik. DC-DC converter merupakan perangkat elektronika daya yang mengubah tegangan DC menjadi level tegangan DC yang berbeda. Makalah ini menyajikan pendekatan untuk DC-DC converter yang terdiri dari perangkat elektronika daya semikonduktor yang berfungsi sebagai switching. Pengoperasian switching ini menyebabkan karakteristik nonlinier pada DC-DC converter. DC-DC converter yang akan dibahas adalah Buck converter ; Boost converter ; Buck-Boost converter, dan Switched-capacitor converter(inductorless converter/charge pumps). Makalah ditulis dalam format IEEE - LaTeX

***Index Terms*—buck converter, boost converter, buck-boost converter, charge pumps, LaTeX**

I. LINEAR VOLTAGE REGULATORS

Salah satu metode mengubah tegangan dc ke tegangan dc yang lebih rendah secara rangkaian sederhana dapat dilihat pada gbr. 1. Tegangan luaran adalah

$$V_o = I_L R_L$$

dimana arus beban dikendalikan oleh transistor. Dengan mengatur arus basis transistor, tegangan luaran dapat dikendali pada kisaran 0 sampai V_s. Arus basis dapat diatur untuk mengimbangi variasi pasokan tegangan atau beban, sehingga tegangan luaran dapat diatur. Jenis rangkaian ini disebut Konverter dc-dc linier atau regulator linier karena transistor bekerja secara linier. Transistor bekerja sebagai resistansi variabel.

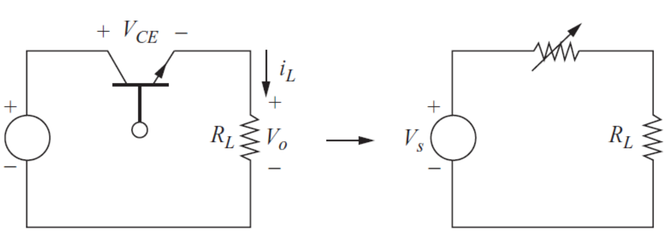


Fig. 1. A basic linear regulator.

II. A BASIC SWITCHING CONVERTER

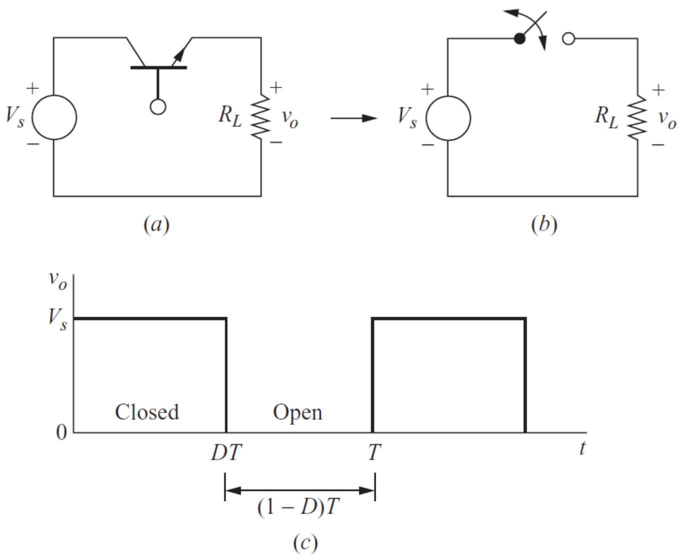


Fig. 2. (a) A basic dc-dc switching converter; (b) Switching equivalent; (c) Output voltage.

Berdasarkan gambar 2(c) Tegangan luaran adalah:

$$\boxed{V_o = \frac{1}{T}\int_0^T V_o(t)\,dt = \frac{1}{T}\int_0^{DT} V_s\,dt = V_s D} \qquad (1)$$

Tegangan luaran dc ditentukan dengan mengatur *duty ratio* D ; dengan f adalah *switching frequency*

$$\boxed{D \equiv \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}} = \frac{t_{\text{on}}}{T} = t_{\text{on}} f} \qquad (2)$$

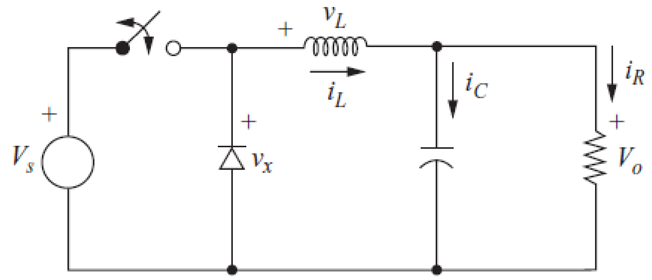
III. THE BUCK (STEP-DOWN) CONVERTER

A. Voltage and Current Relationships

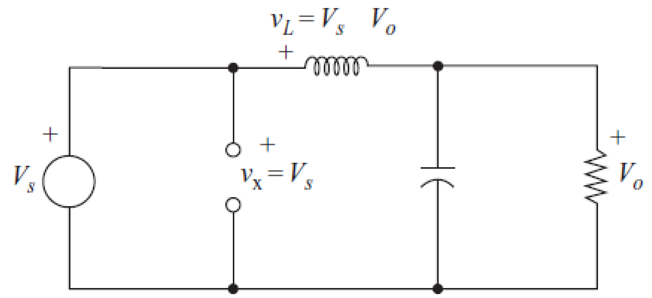
$$i_L(t+T) = i_L(t) \qquad (3)$$

$$V_L = \frac{1}{T}\int_t^{t+T} V_L(\lambda)\,d(\lambda) = 0 \qquad (4)$$

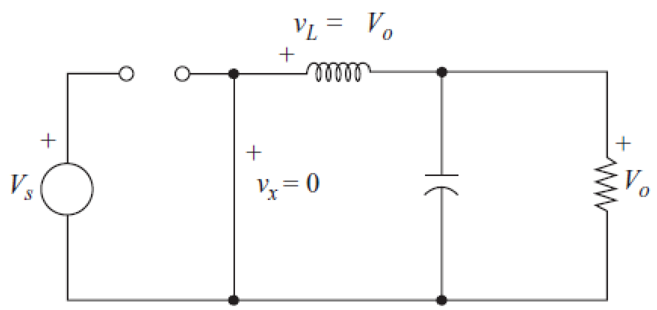
The average capacitor current is zero



(a)



(b)



(c)

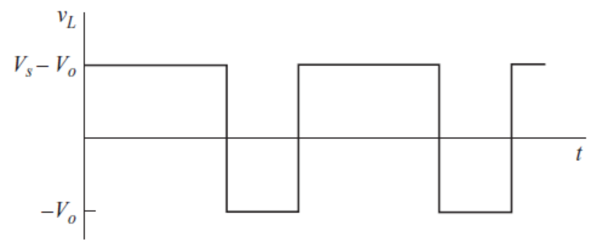
Fig. 3. (a) Buck dc-dc converter; (b) Equivalent circuit for the switch closed; (c) Equivalent circuit for the switch open.

$$I_C = \frac{1}{T}\int_t^{t+T} i_C(\lambda)\, d(\lambda) = 0 \tag{5}$$

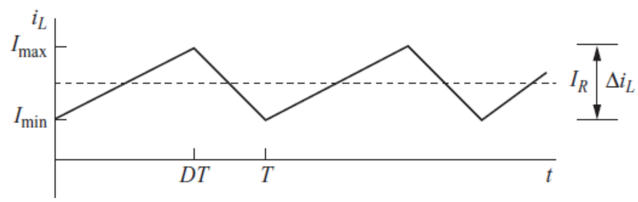
The power supplied by the source is the same as the power delivered to the load. For nonideal components, the source also supplies the losses.

$$\begin{aligned} P_s &= P_o && \text{ideal} \\ P_s &= P_o + \text{losses} && \text{non ideal} \end{aligned} \tag{6}$$

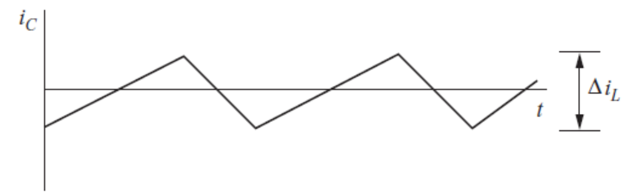
B. Analysis for the Switch Closed



(a)



(b)



(c)

Fig. 4. Buck converter waveforms: (a) Inductor voltage; (b) Inductor current; (c) Capacitor current.

$$v_L = V_s - V_o = L\frac{di_L}{dt}$$

$$\begin{gathered} \frac{di_L}{dt} = \frac{V_s - V_o}{L} \qquad \text{switch closed} \\ \frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s - V_o}{L} \\ (\Delta i_L)_{\text{closed}} = \left(\frac{V_s - V_o}{L}\right) DT \end{gathered} \tag{7}$$

C. Analysis for the Switch Open

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

$$\frac{di_L}{dt} = \frac{-V_o}{L} \qquad \text{switch open}$$

$$\begin{gathered} \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = -\frac{V_o}{L} \\ (\Delta i_L)_{\text{open}} = -\left(\frac{V_o}{L}\right)(1-D)T \end{gathered} \tag{8}$$

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

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

$$\boxed{V_o = V_s D} \tag{9}$$

$$V_L = (V_s - V_o)DT + (-V_o)(1-D)T = 0$$

$$I_L = I_R = \frac{V_o}{R} \tag{10}$$

$$\begin{aligned} I_{\max} &= I_L + \frac{\Delta i_L}{2} \\ &= \frac{V_o}{R} + \frac{1}{2}\left[\frac{V_o}{L}(1-D)T\right] = V_o\left(\frac{1}{R} + \frac{1-D}{2Lf}\right) \end{aligned} \tag{11}$$

$$\begin{aligned} I_{\min} &= I_L - \frac{\Delta i_L}{2} \\ &= \frac{V_o}{R} - \frac{1}{2}\left[\frac{V_o}{L}(1-D)T\right] = V_o\left(\frac{1}{R} - \frac{1-D}{2Lf}\right) \end{aligned} \tag{12}$$

dimana $f = 1/T$ adalah frekuensi switching

$$\begin{aligned} I_{\min} = 0 &= V_o\left(\frac{1}{R} - \frac{1-D}{2Lf}\right) \\ (Lf)_{\min} &= \frac{(1-D)R}{2} \end{aligned} \tag{13}$$

$$\boxed{L_{\min} = \frac{(1-D)R}{2f} \qquad \text{for continuous current}} \tag{14}$$

$$\begin{aligned} \Delta i_L &= \left(\frac{V_s - V_o}{L}\right)DT = \left(\frac{V_s - V_o}{Lf}\right)D \\ &= \frac{V_o(1-D)}{Lf} \end{aligned} \tag{15}$$

atau

$$\boxed{L = \left(\frac{V_s - V_o}{\Delta i_L f}\right)D = \frac{V_o(1-D)}{\Delta i_L f}} \tag{16}$$

$$\begin{aligned} P_s &= P_o \\ V_s I_s &= V_o I_o \end{aligned} \tag{17}$$

atau

$$\frac{V_o}{V_s} = \frac{I_s}{I_o}$$

D. *Riak Tegangan Luaran*

Variasi pada tegangan output atau riak merupakan selisih dari tegangan-arus pada kapasitor. Arus pada kapasitor adalah

$$i_C = i_L - i_R$$

$$Q = CV_o$$

$$\Delta Q = C\Delta V_o$$

$$\Delta V_o = \frac{\Delta Q}{C}$$

$$\Delta Q = \frac{1}{2}\left(\frac{T}{2}\right)\left(\frac{\Delta i_L}{2}\right) = \frac{T\Delta i_L}{8}$$

$$\Delta V_o = \frac{T\Delta i_L}{8C}$$

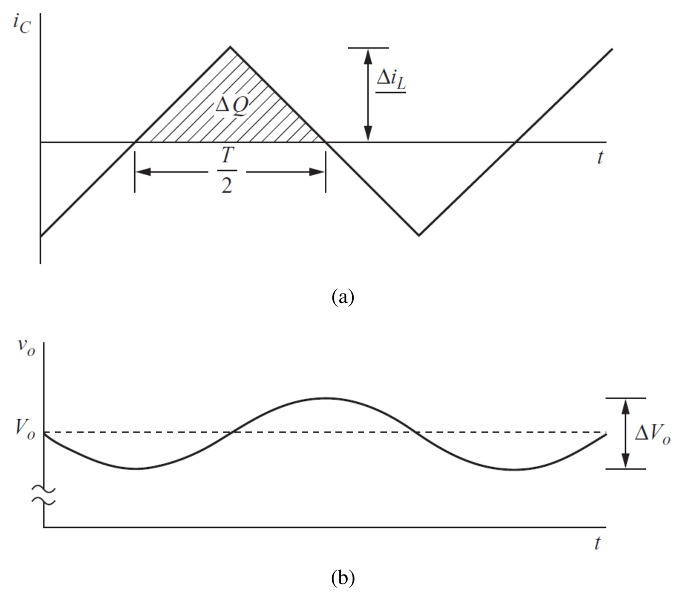


Fig. 5. Gelombang buck converter. (a) Arus kapasitor ; (b) Riak tegangan kapasitor.

$$\Delta V_o = \frac{T\,V_o}{8CL}(1-D)T = \frac{V_o(1-D)}{8LCf^2} \tag{18}$$

$$\boxed{\frac{\Delta V_o}{V_o} = \frac{1-D}{8LCf^2}} \tag{19}$$

$$\boxed{C = \frac{1-D}{8L(\Delta V_o/V_o)f^2}} \tag{20}$$

IV. THE BOOST CONVERTER

A. Voltage and Current Relationships

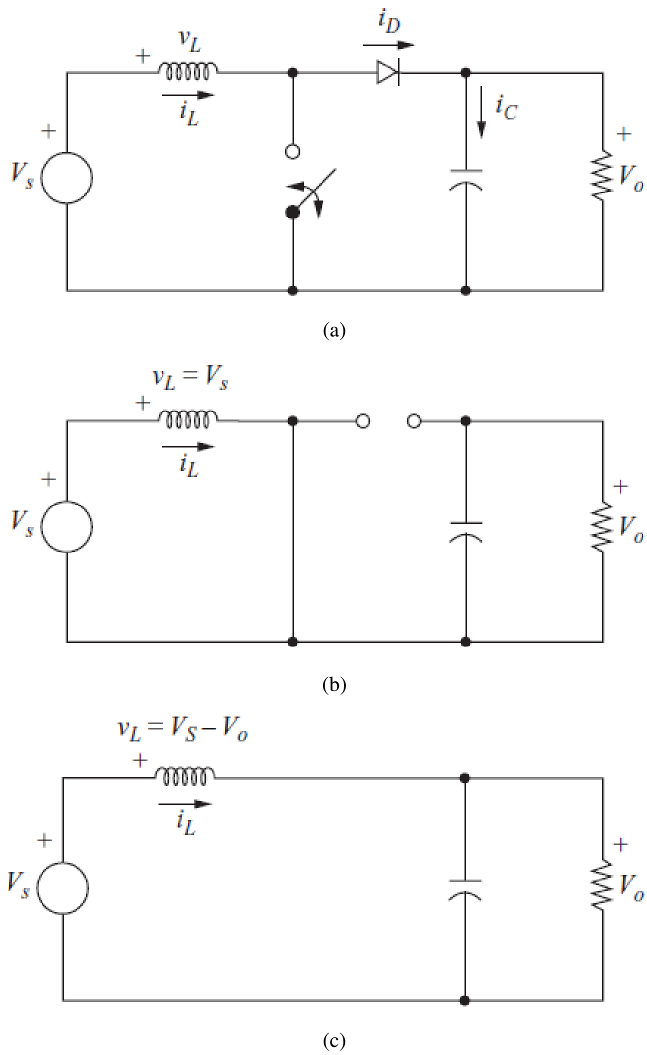


Fig. 6. The boost converter. (a) Circuit; (b) Equivalent circuit for the switch closed; (c) Equivalent circuit for the switch open.

B. Analysis for the Switch Closed

$$v_L = V_s = L\frac{di_L}{dt} \quad atau \quad \frac{di_L}{dt} = \frac{V_s}{L} \tag{21}$$

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L}$$

penyelesaian untuk Δi_L

$$(\Delta i_L)_{\text{closed}} = \frac{V_s DT}{L} \tag{22}$$

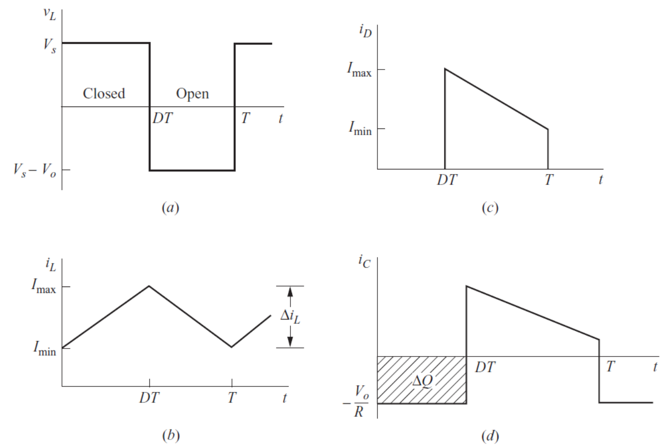


Fig. 7. Boost converter waveforms. (a) Inductor voltage; (b) Inductor current; (c) Diode current; (d) Capacitor current.

C. Analysis for the Switch Open

$$v_L = V_s - V_o = L\frac{di_L}{dt}$$

$$\frac{di_L}{dt} = \frac{V_s - V_o}{L}$$

$$\begin{aligned} \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} &= \frac{V_s - V_o}{L} \\ (\Delta i_L)_{\text{open}} &= \frac{(V_s - V_o)(1-D)T}{L} \end{aligned} \tag{23}$$

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

$$\frac{V_s DT}{L} + \frac{(V_s - V_o)(1-D)T}{L} = 0$$

$$V_s(D + 1 - D) - V_o(1-D) = 0$$

$$\boxed{V_o = \frac{V_s}{1-D}} \tag{24}$$

$$V_L = V_s D + (V_s - V_o)(1-D) = 0$$

Daya luaran:

$$P_o = \frac{V_o^2}{R} = V_o I_o$$

daya input adalah $V_s I_s = V_s I_L$. samakan daya input dan daya output, diperoleh

$$V_s I_L = \frac{V_o^2}{R} = \frac{[V_s/(1-D)]^2}{R} = \frac{V_s^2}{(1-D)^2}R$$

$$\boxed{I_L = \frac{V_s}{(1-D)^2 R} = \frac{V_o^2}{V_s R} = \frac{V_o I_o}{V_s}} \tag{25}$$

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2R} + \frac{V_sDT}{2L} \qquad (26)$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = \frac{V_s}{(1-D)^2R} - \frac{V_sDT}{2L} \qquad (27)$$

$$I_{\min} = 0 = \frac{V_s}{(1-D)^2R} - \frac{V_sDT}{2L}$$

atau

$$\frac{V_s}{(1-D)^2R} = \frac{V_sDT}{2L} = \frac{V_sD}{2Lf}$$

$$(Lf)_{min} = \frac{D(1-D)^2R}{2} \qquad (28)$$

atau

$$\boxed{L_{min} = \frac{D(1-D)^2R}{2f}} \qquad (29)$$

$$L = \frac{V_sDT}{\Delta i_L} = \frac{V_sD}{\Delta i_L f}$$

D. Output Voltage Ripple

$$\Delta Q = \left(\frac{V_o}{R}\right) DT = C\Delta V_o$$

$$\Delta V_o = \frac{V_oDT}{RC} = \frac{V_oD}{RCf}$$

atau

$$\boxed{\frac{\Delta V_o}{V_o} = \frac{D}{RCf}} \qquad (30)$$

$$C = \frac{D}{R(\Delta V_o/V_o)f} \qquad (31)$$

$$\Delta V_{o,\text{ESR}} = \Delta i_C r_C = I_{L,\max} r_C \qquad (32)$$

V. THE BUCK-BOOST CONVERTER

A. Voltage and Current Relationships

Beberapa hal yang diasumsikan:

1) Rangkaian bekerja keadaan steady state
2) Arus induktor kontinyu
3) Kapasitor cukup besar agar diperoleh tegangan luaran konstan
4) Switch keadaan tertutup pada saat DT dan terbuka (1-D)T
5) Komponen-komponen adalah ideal.

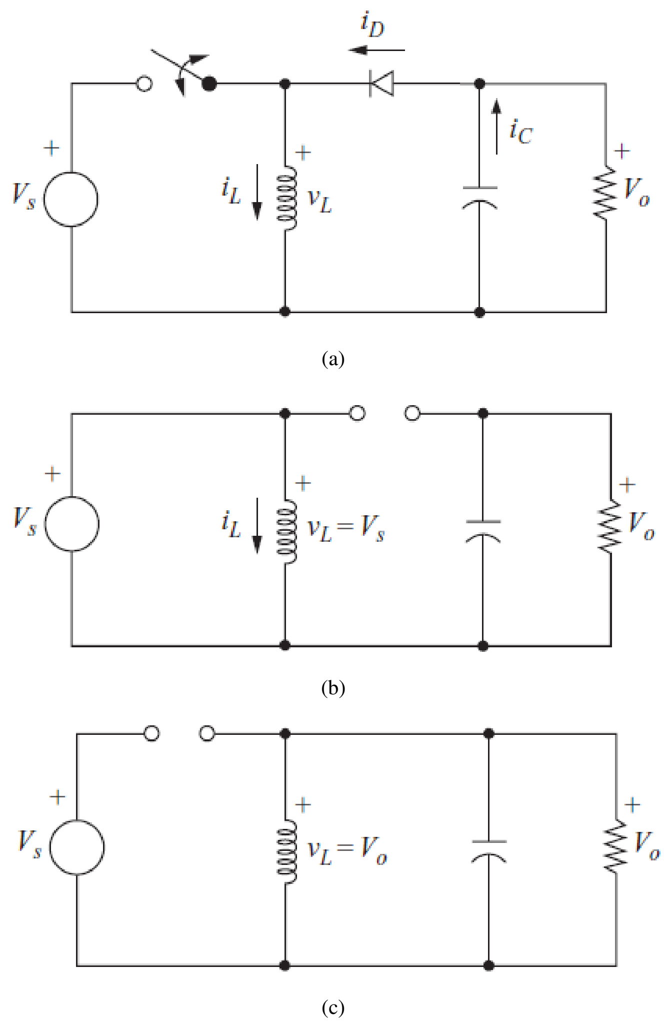


Fig. 8. Buck-boost converter. (a) Circuit; (b) Equivalent circuit for the switch closed; (c) Equivalent circuit for the switch open.

B. Analysis for the Switch Closed

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

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

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_s}{L}$$

$$(\Delta i_L)_{\text{closed}} = \frac{V_s DT}{L} \tag{33}$$

C. Analysis for the Switch Open

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

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

$$\frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_o}{L}$$

penyelesaian untuk Δi_L,

$$(\Delta i_L)_{\text{open}} = \frac{V_o(1-D)T}{L} \tag{34}$$

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

$$\frac{V_s DT}{L} + \frac{V_o(1-D)T}{L} = 0$$

$$\boxed{V_o = -V_s\left(\frac{D}{1-D}\right)} \tag{35}$$

$$D = \frac{|V_o|}{V_s + |V_o|} \tag{36}$$

$$V_L = V_s D + V_o(1-D) = 0$$

$$P_o = \frac{V_o^2}{R}$$

$$P_s = V_s I_s$$

$$\frac{V_o^2}{R} = V_s I_s$$

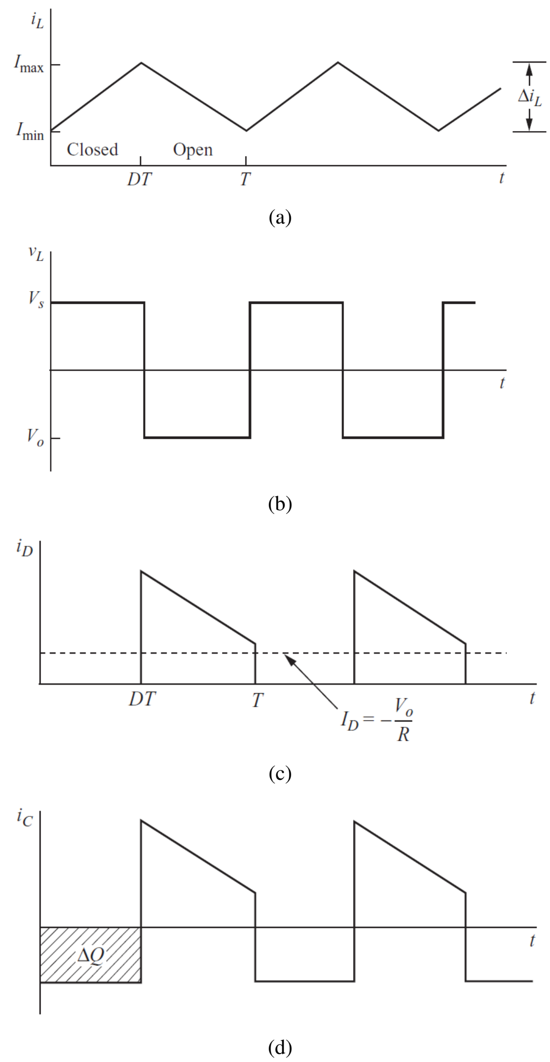


Fig. 9. Buck-boost converter waveforms. (a) Inductor current; (b) Inductor voltage; (c) Diode current; (d) Capacitor current.

$$I_s = I_L D$$

$$\frac{V_o^2}{R} = V_s I_L D$$

$$I_L = \frac{V_o^2}{V_s R D} = \frac{P_o}{V_s D} = \frac{V_s D}{R(1-D)^2} \tag{37}$$

$$I_{\text{max}} = I_L + \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} + \frac{V_s DT}{2L} \tag{38}$$

$$I_{\text{min}} = I_L - \frac{\Delta i_L}{2} = \frac{V_s D}{R(1-D)^2} - \frac{V_s DT}{2L} \tag{39}$$

$$(Lf)_{\text{min}} = \frac{(1-D)^2 R}{2} \tag{40}$$

atau

$$\boxed{L_{\text{min}} = \frac{(1-D)^2 R}{2f}} \tag{41}$$

D. Output Voltage Ripple

$$|\Delta Q| = \left(\frac{V_o}{R}\right) DT = C\Delta V_o$$

penyelesaian untuk ΔV_o,

$$\Delta V_o = \frac{V_o DT}{RC} = \frac{V_o D}{RCf}$$

atau

$$\boxed{\frac{\Delta V_o}{V_o} = \frac{D}{RCf}} \tag{42}$$

$$\Delta V_{o,\text{ESR}} = \Delta i_C r_C = I_{L,\max} r_C \tag{43}$$

VI. SWITCHED-CAPACITOR CONVERTERS (INDUCTORLESS CONVERTERS OR CHARGE PUMPS)

A. The Step-Up Switched-Capacitor Converter

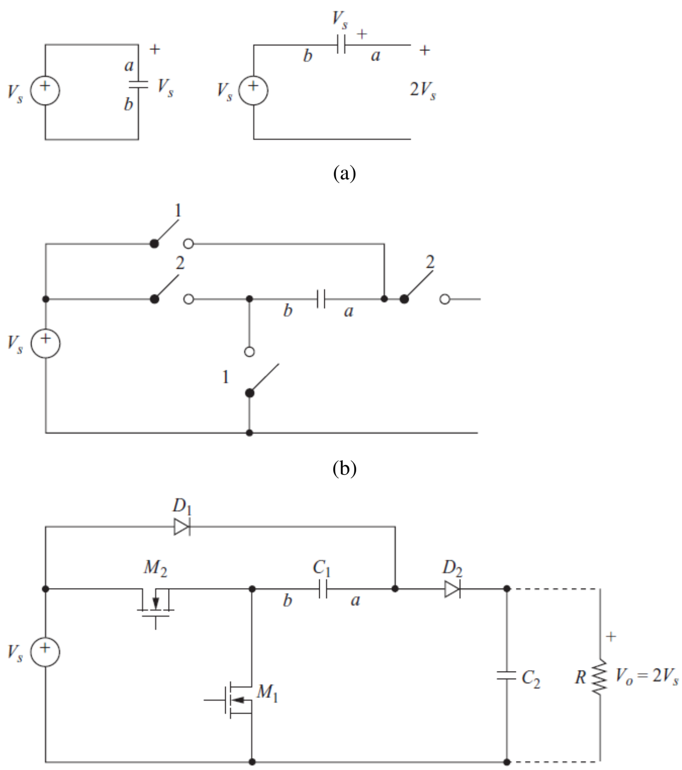


Fig. 10. A switched-capacitor step-up converter. (a) A capacitor is charged and then reconnected to produce a voltage of twice that of the source; (b) A switch arrangement; (c) An implementation using transistors and diodes and showing a second capacitor C2 to sustain the output voltage during switching.

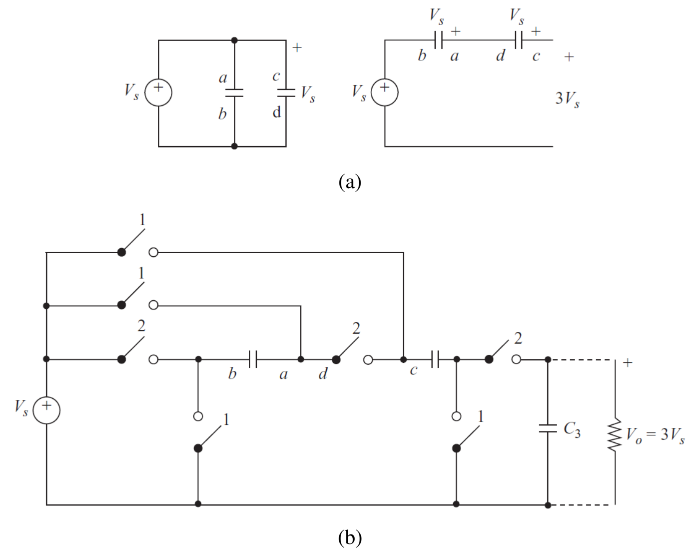


Fig. 11. A step-up switched-capacitor converter to produce 3 times the source voltage. (a) Each capacitor is charged to V_s and reconnected to produce an output of $3V_s$; (b) A switch arrangement also shows an output capacitor to sustain the output voltage during switching.

B. The Inverting Switched-Capacitor Converter

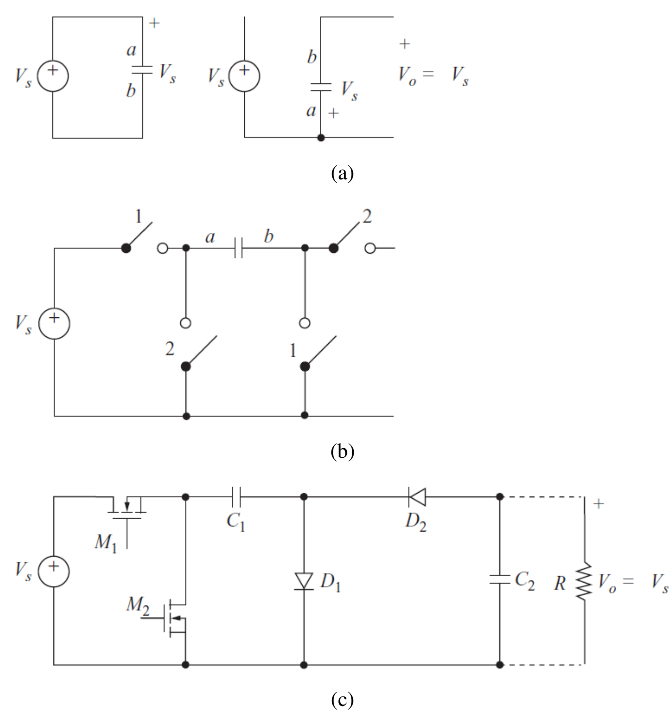


Fig. 12. The inverting switched-capacitor converter. (a) The capacitor is charged to V_s and then reconnected to produce an output of $-V_s$; (b) A switch arrangement; (c) An implementation using transistors and diodes and showing a second capacitor to sustain the output voltage during switching.

C. The Step-Down Switched-Capacitor Converter

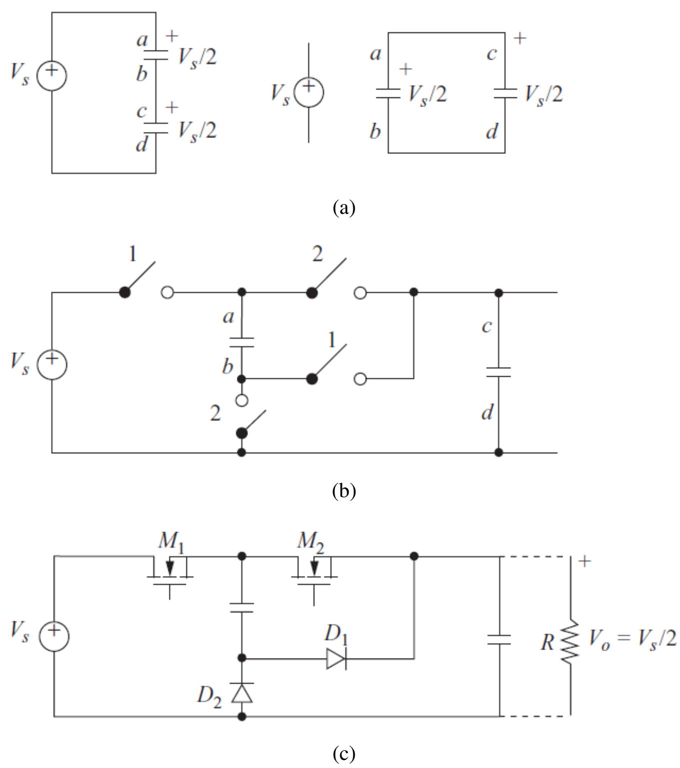


Fig. 13. The step-down switched-capacitor converter. (a) The capacitors are in series and each is charged to $V_s/2$, followed by the capacitors in parallel, with the output voltage at $V_s/2$; (b) A switch arrangement; (c) An implementation using transistors and diodes.

LATIHAN

Rancangan sebuah buck converter dengan tegangan luaran 18 V yang melewati resistor beban 10 Ω. Riak (ripple) tegangan luaran tidak melebihi 0,5%. Catu daya DC adalah 48 V maka akan ditentukan *duty ratio* (D), frekuensi switching, nilai induktor dan kapasitor. Asumsikan semua komponen adalah ideal.

Dari persamaan (9), diperoleh:

$$D = \frac{V_o}{V_s} = \frac{18}{48} = 0,375$$

Frekuensi switching adalah 40 kHz yang berada diatas frekuensi audio dan cukup rendah untuk menghasilkan rugi-rugi switching.

Nilai induktor diperoleh dari persamaan (14):

$$L_{\text{min}} = \frac{(1-D)(R)}{2f} = \frac{(1-0,375)(10)}{2(40.000)} = 78\,\mu H$$

nilai L adalah 25% lebih besar, maka:

$$L = 1,25 L_{\text{min}} = (1,25)(78\,\mu H) = 97,5\,\mu H$$

Nilai kapasitor dari persamaan (20) adalah:

$$C = \frac{(1-D)}{8L(\Delta V_o/V_o)f^2} = \frac{(1-0,375)}{8(97,5)(10)^{-6}(0,005)(40.000)^2} = 100\,\mu F$$

TABLE I
PARAMETER BUCK CONVERTER

No.	Parameter	Nilai
1	V_s	48 V
2	V_o	18 V
3	D	0.375
4	R	10 Ω
5	L	97.5 μH
6	C	100 μF
7	f	40 kHz

Simulasi

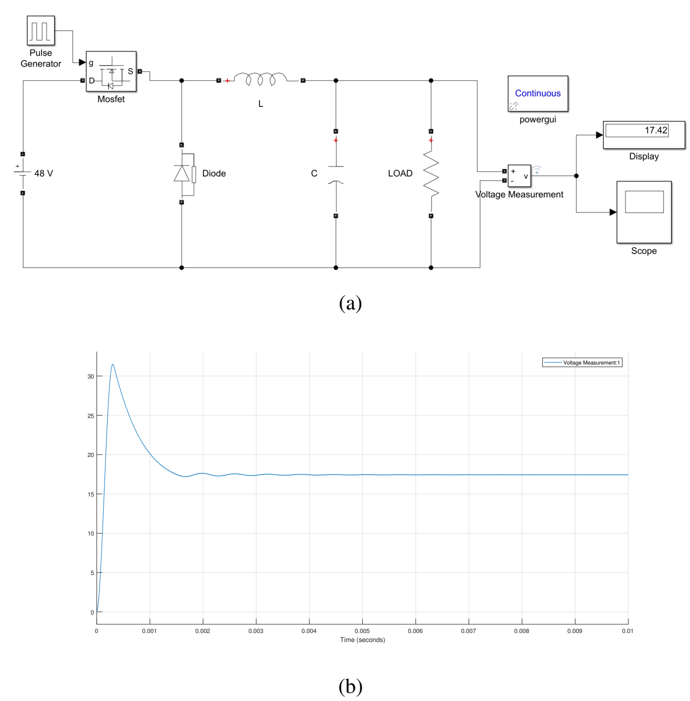


Fig. 14. Buck converter open loop. (a) Rangkaian ; (b) Tegangan luaran.

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