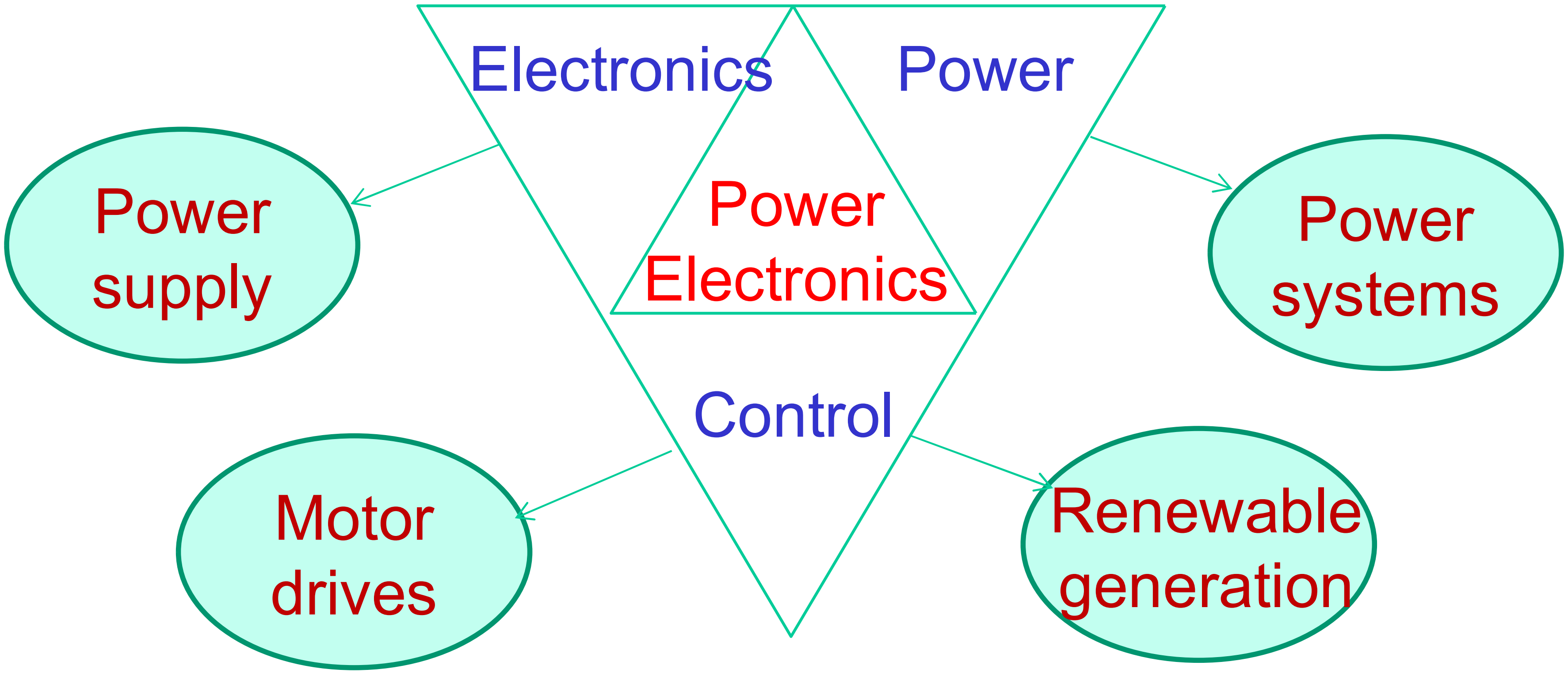
Power Electronics
Applications



SUN Kai 孙凯

Power Electronics

Chap. 10

Switching DC Power Supply

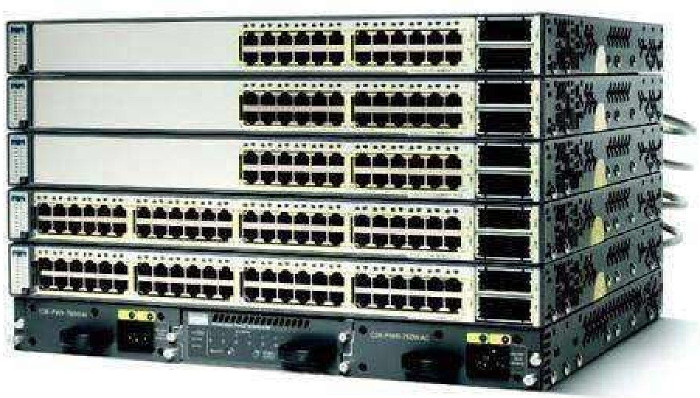
Outlines

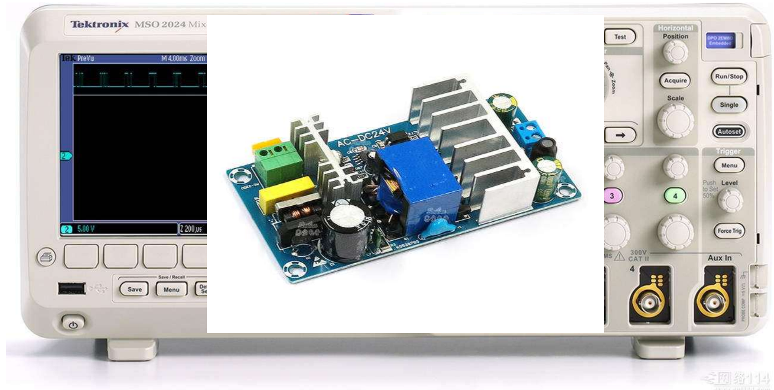
- Introduction
- Linear Power Supplies
- Overview of Switching Power Supplies
- dc-dc Converters with Electrical Isolation
- Control of Switch-Mode Power Supplies
- Summary & Discussion

Chap.10 Switching dc Power Supply

Introduction

Applications of dc Power Supplies





Electronic Instruments

Lighting

Program-controlled Switchboards

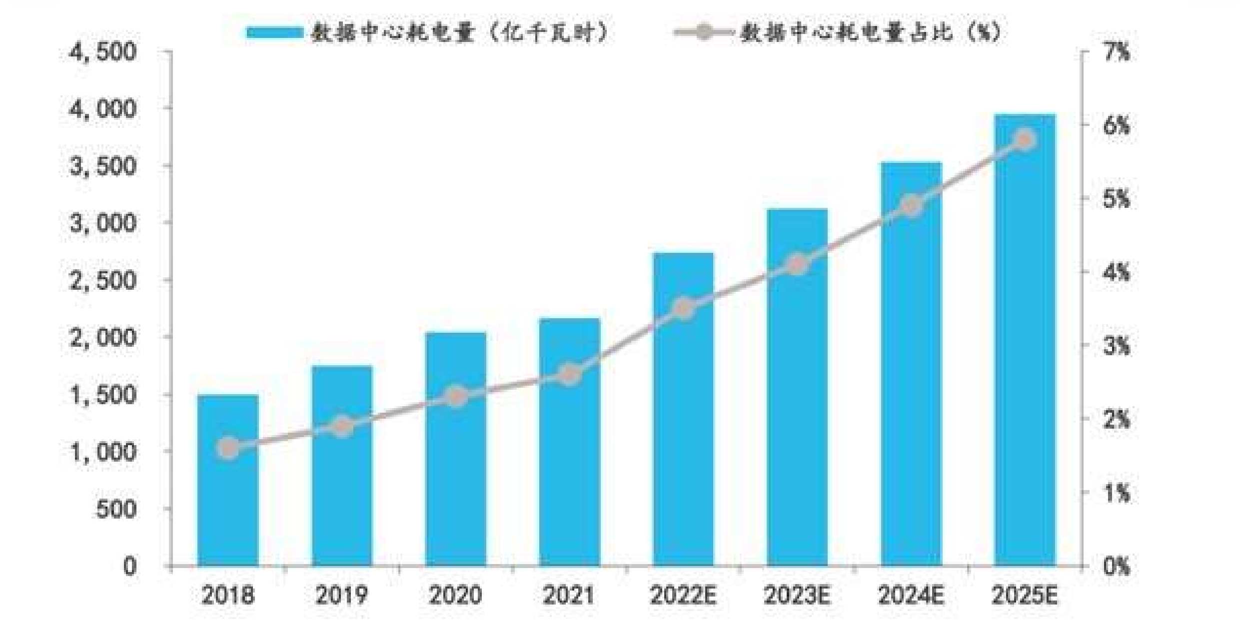
Consumer electronic products

Introduction

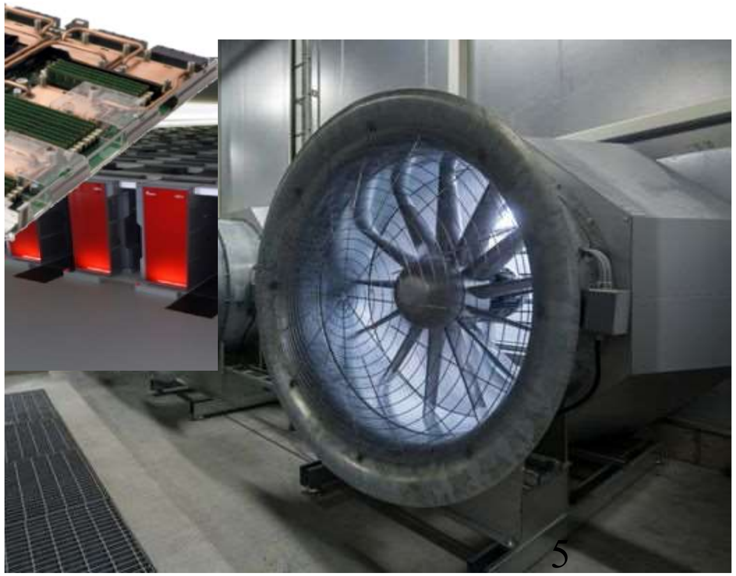
Applications of dc Power Supplies

Data Center

图10. 全国数据中心耗电量（左轴）与数据中心耗电量占全国用电量比重（右轴）



资料来源：工业和信息化部，中国 IDC 圈，安信证券研究中心



Introduction

Requirements for dc Power Supplies

Regulated output: The output voltage must be held constant within a specified tolerance for changes within a specified range in the input voltage and the output loading.

Isolation: The output voltage may be required to be electrically isolated from the input.

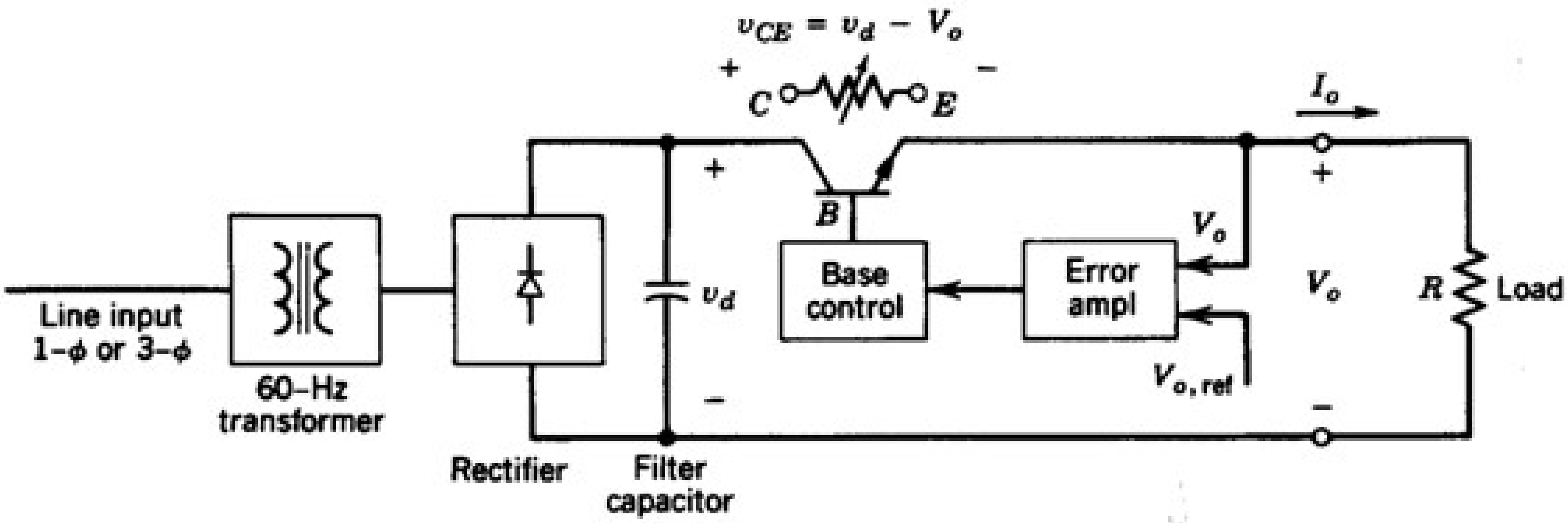
Multiple output: There may be multiple outputs that may differ in their voltage and current ratings.

- Common goals are to *reduce power supply size and weight* and *improve their efficiency.*

Linear Power Supplies

- The control circuit adjusts the transistor base current such $V_o (= v_d - v_{CE})$ equals $V_{o,ref}$.

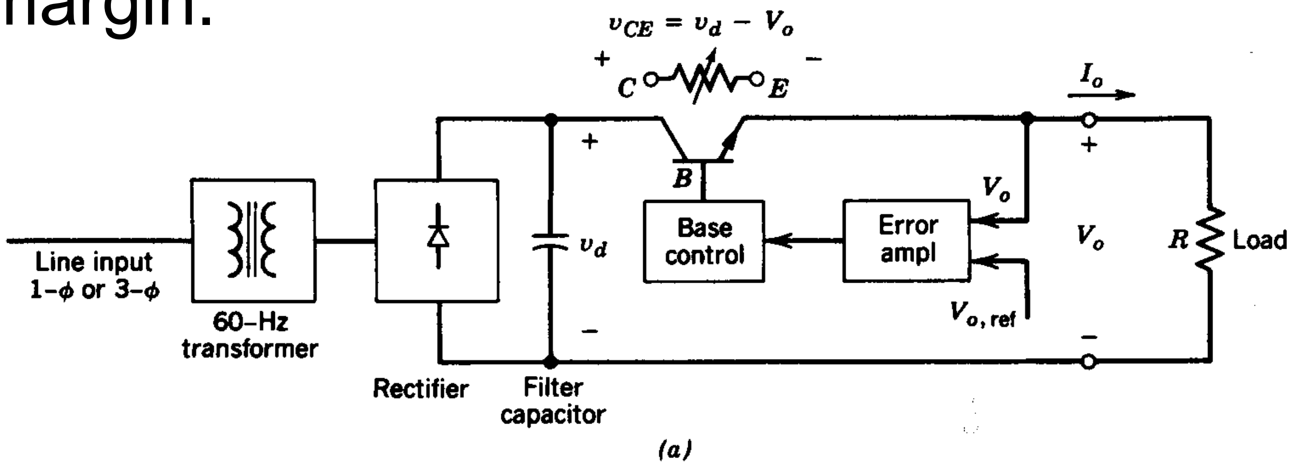
- The transistor in a linear power supply works in its active region and acts as an adjustable resistor.



(a)

Linear Power Supplies

- To minimize the transistor power losses, the transformer turns ratio should be carefully selected so that $V_{d,\min} > V_o$ by a small margin.



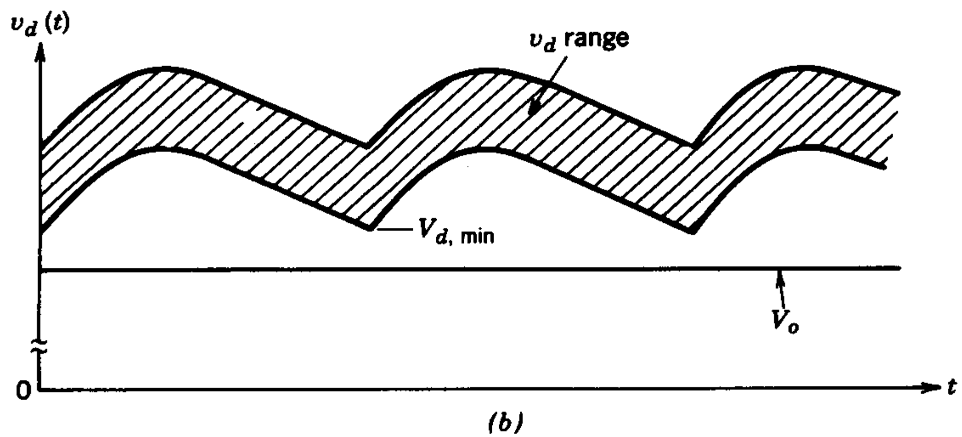


Figure 10-1 Linear power supply: (*a*) schematic; (*b*) selection of transformer turns ratio so that $V_{d,\min} > V_o$ by a small margin.

Linear Power Supplies

Major shortcomings of a linear power supply

A low-frequency (50/60Hz) transformer is required. Such transformers are larger in size and weight compared to high-frequency transformers.

The transistor operates in its active region, incurring a significant amount of power loss. Therefore, the overall efficiencies of linear power supplies are usually in a range of 30-60%.

Chap.10 Switching dc Power Supply

Overview of Switching Power Supplies

• In switching power supplies, the transformation of dc voltage from one level to another is accomplished by using dc-to-dc converters.

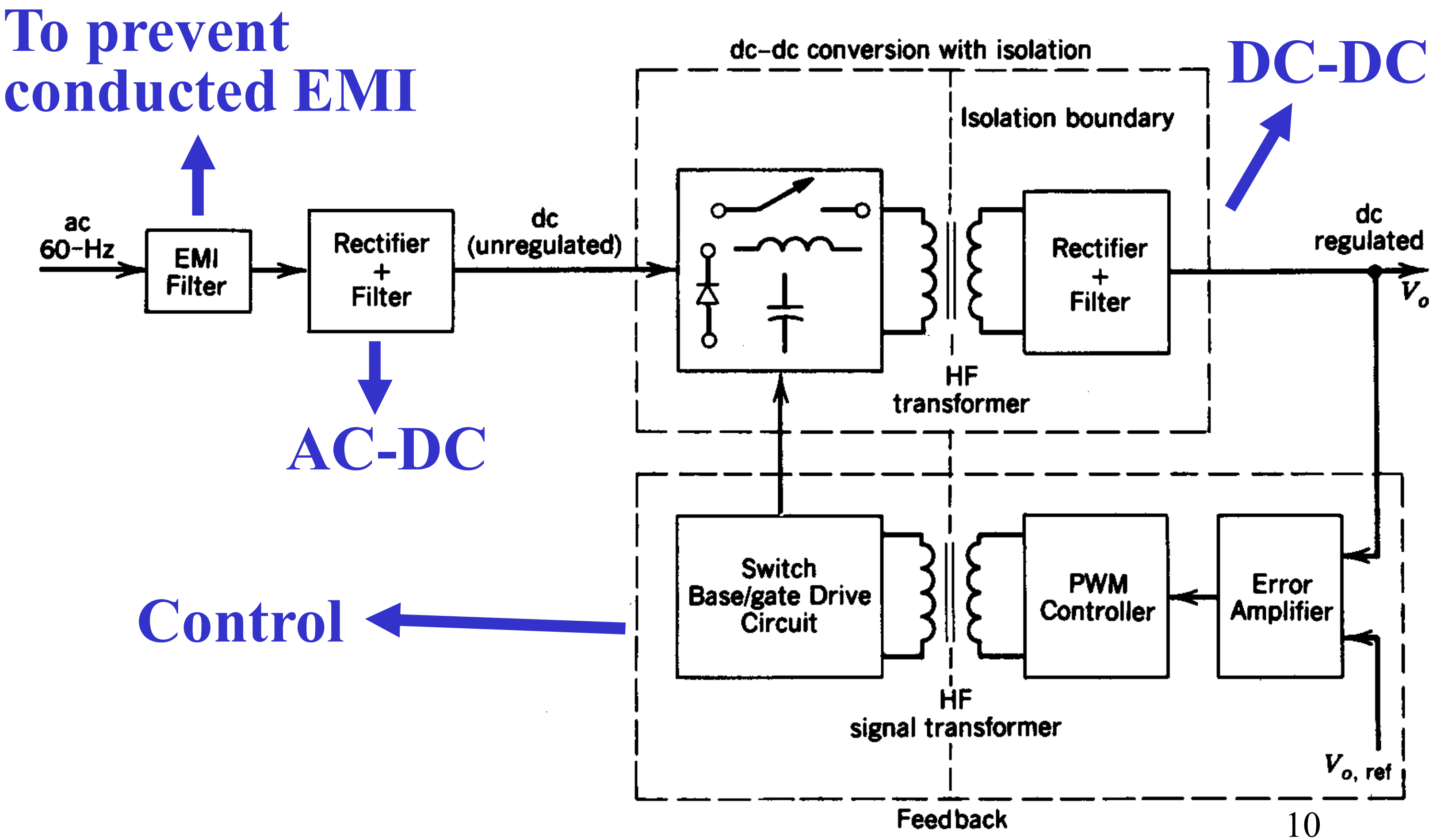


Figure 10-2 Schematic of a switch-mode dc power supply.

Overview of Switching Power Supplies

A - Bridge rectifier

B - Input filter capacitors

between B and C – Heatsink of high-voltage transistors

C - Transformer

between C and D - Heatsink of low-voltage, high-current rectifiers

D - Output filter coil

E - Output filter capacitors

Overview of Switching Power Supplies

• In many applications, multiple outputs (both positive and negative) are required. These outputs may be required to be electrically isolated from each other.

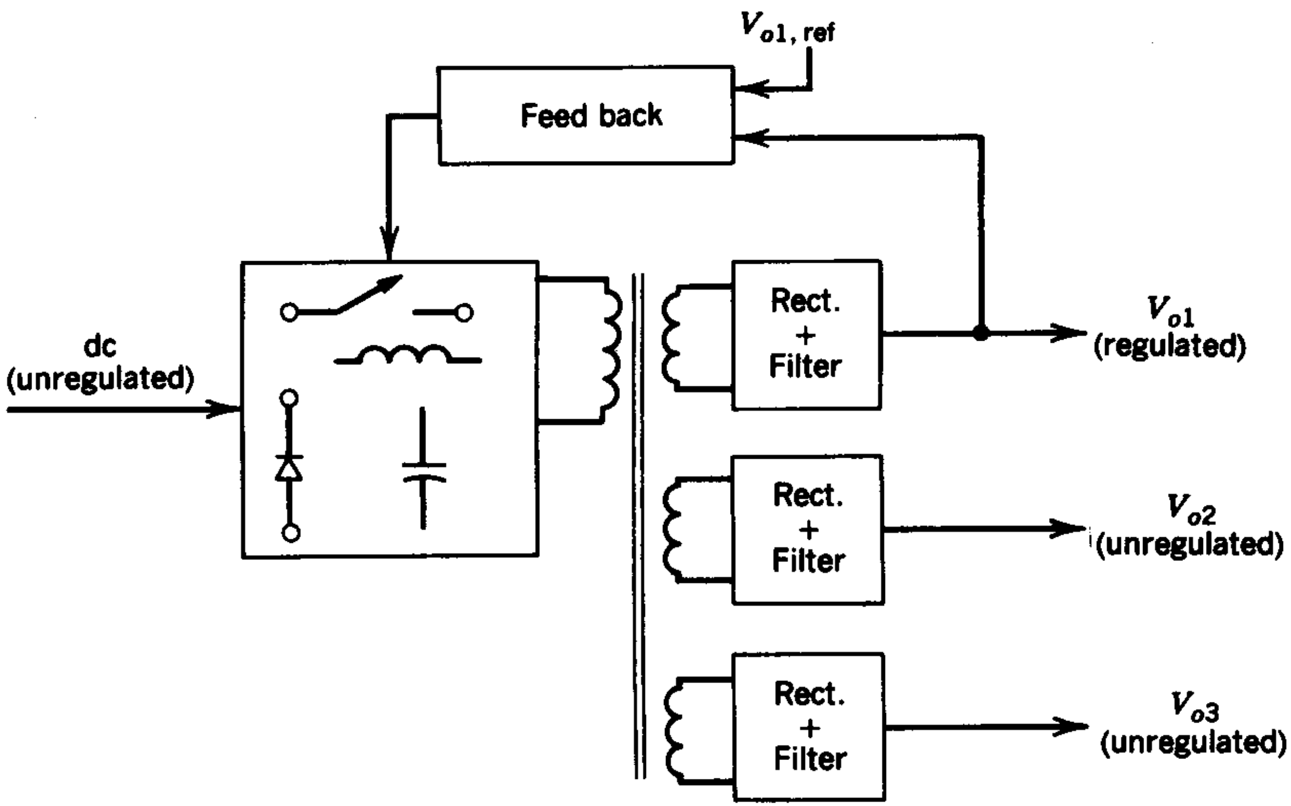
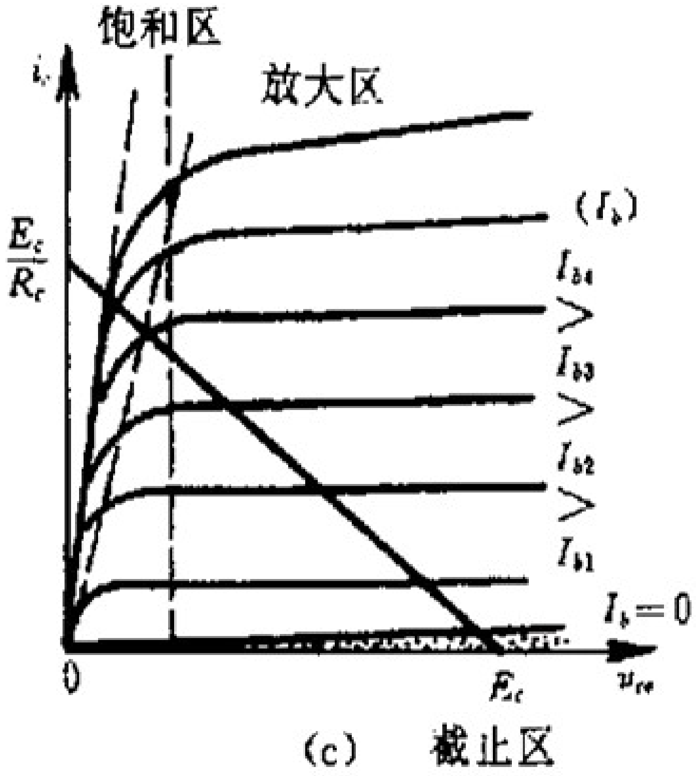


Figure 10-3 Multiple outputs.

Major advantages of switching power supplies

• The switching elements (power transistors or MOSFETs) operate as a switch: either completely off or completely on. By avoiding their o| egion, a significant reduction in power s results in a higher energy efficiency.



• Since a high-freq mer is used (as compared to a 50- a linear power supply), the size ar upplies can be significantly reduce

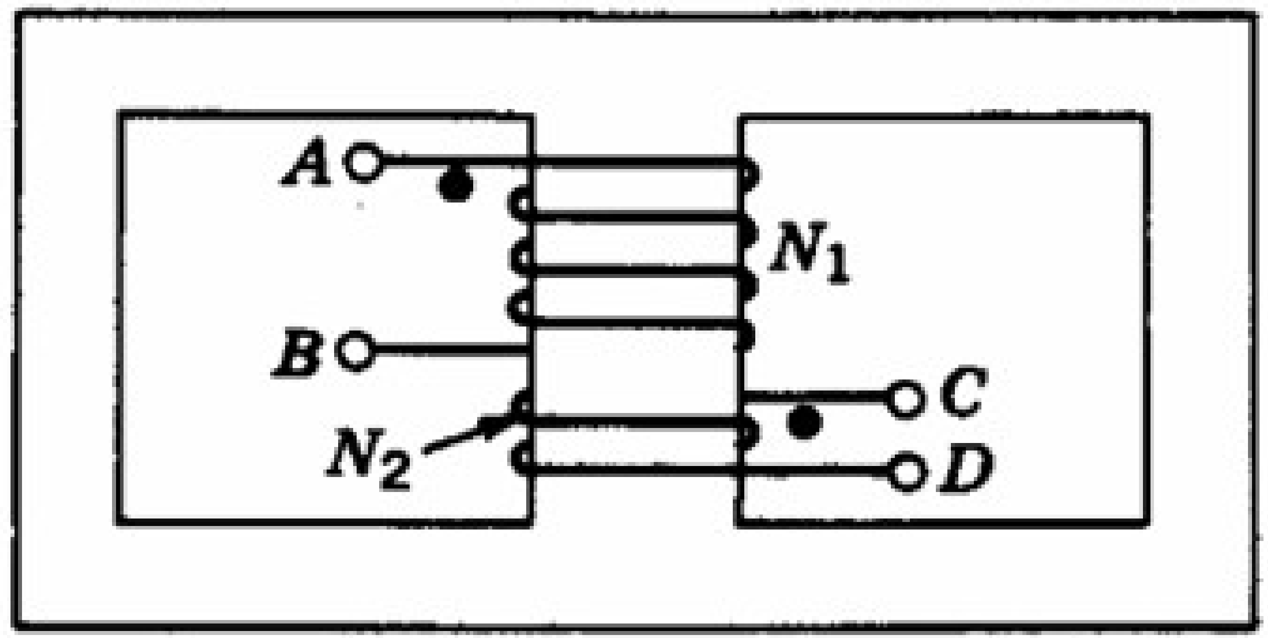
Negative side

• Switching supplies are more complex, and proper measures must be taken to prevent EMI due to high-frequency switchings.

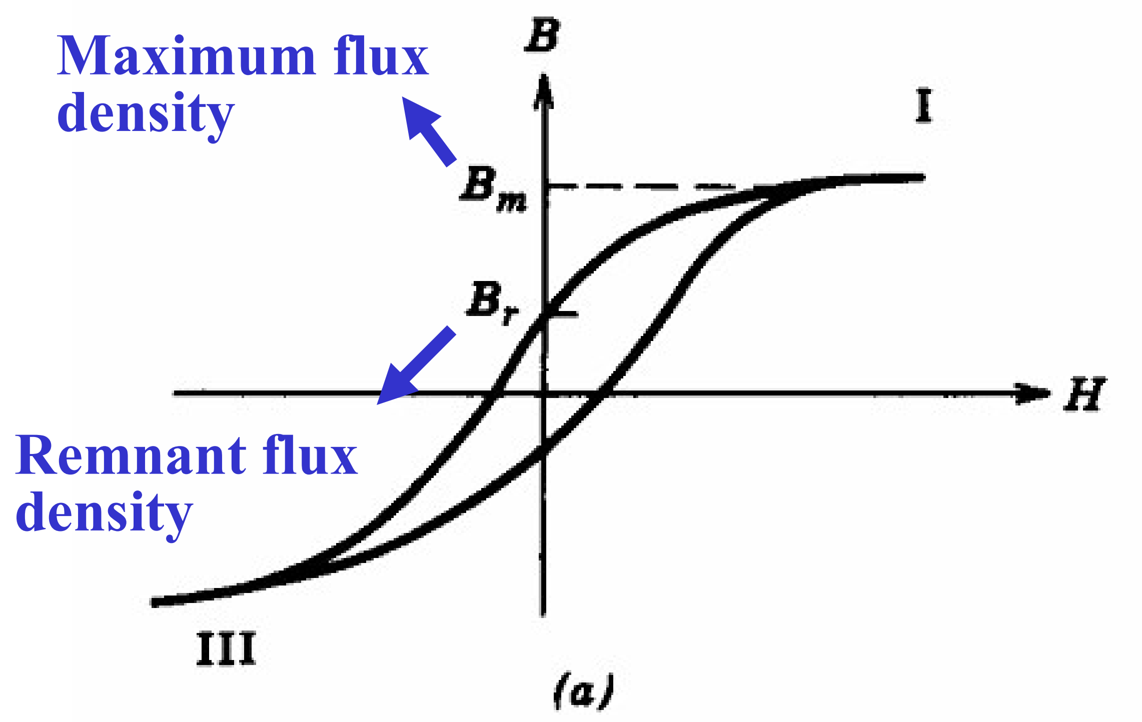
dc-dc Converters with Electrical Isolation

10.4.1 Introduction to dc-dc Converters with Isolation

• The electrical isolation in switching dc power supplies is provided by a high-frequency isolation transformer.



Typical *B-H* loop of transformer core



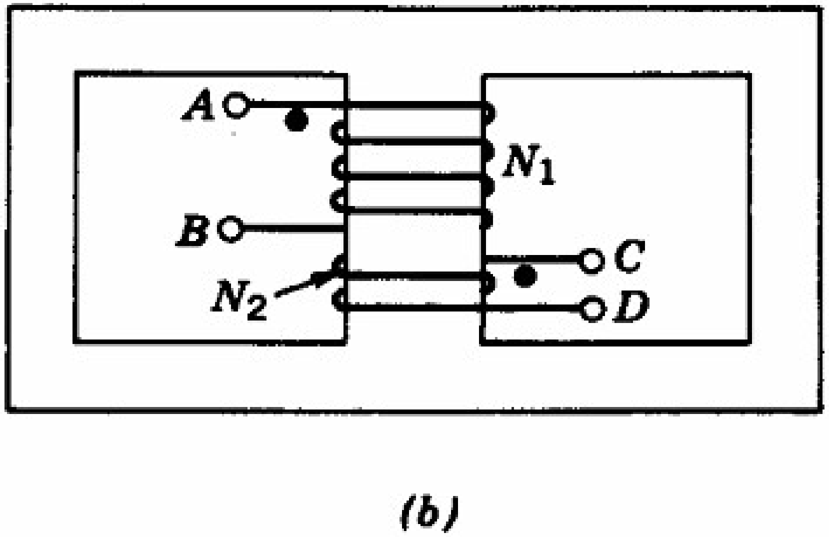
dc-dc converters with isolation

Unidirectional core excitation: only the quadrant 1 of the *B-H* loop is used;

Flyback converter *Forward converter*

Bidirectional core excitation: both the quadrant 1 and quadrant 3 of the *B-H* loop are utilized alternatively;

Push-pull *Half bridge* *Full bridge*



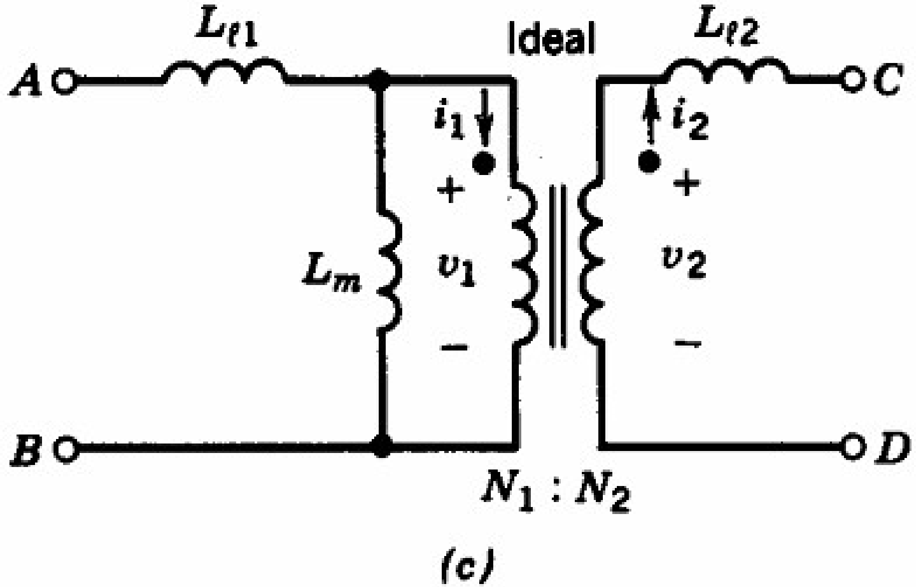


Figure 10-4 Transformer representation: (*a*) typical *B–H* loop of transformer core; (*b*) two-winding transformer; (*c*) equivalent circuit.

- In the ideal transformer,

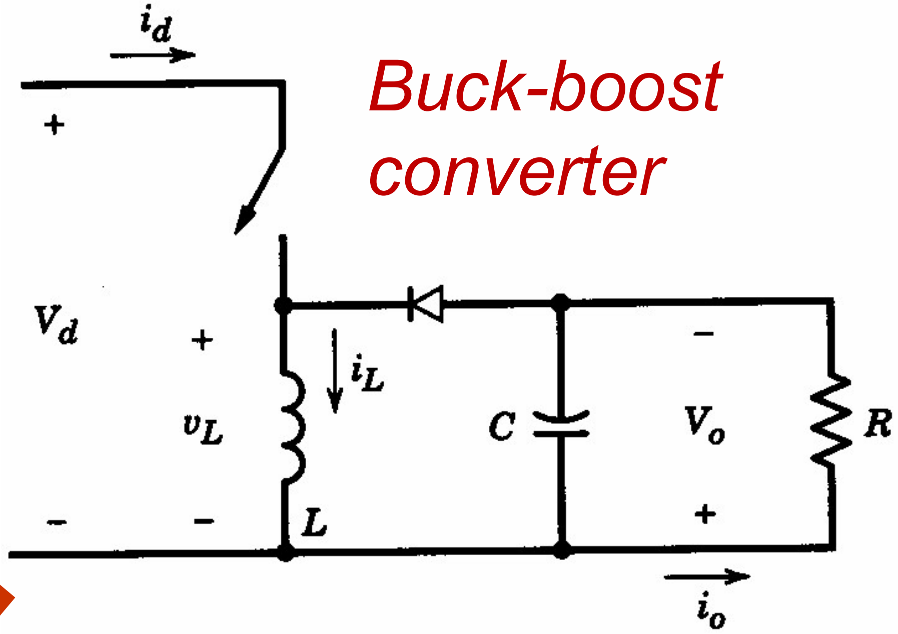
$$v_1 / v_2 = N_1 / N_2 \qquad i_1 N_1 = i_2 N_2$$

- It is desirable to minimize the leakage inductances L_{l1} and L_{l2} by providing a tight magnetic coupling between the two windings.

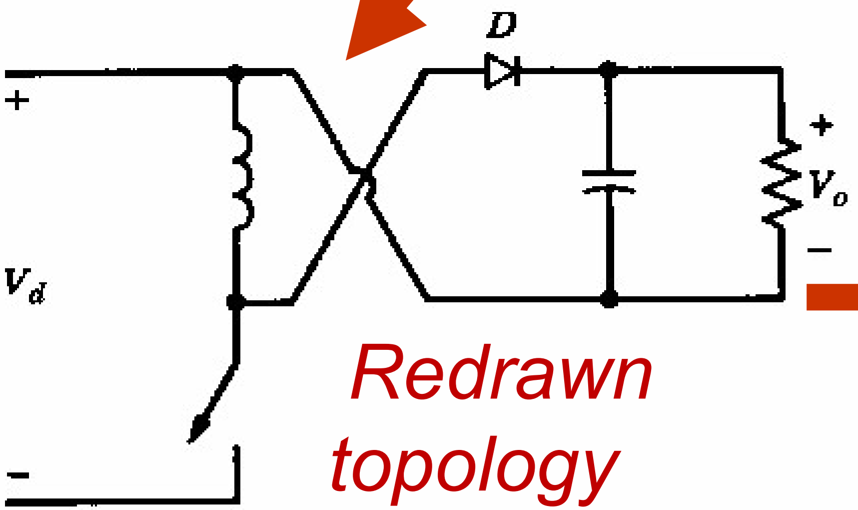
Chap.10 Switching dc Power Supply

— dc-dc Converters with Electrical Isolation —

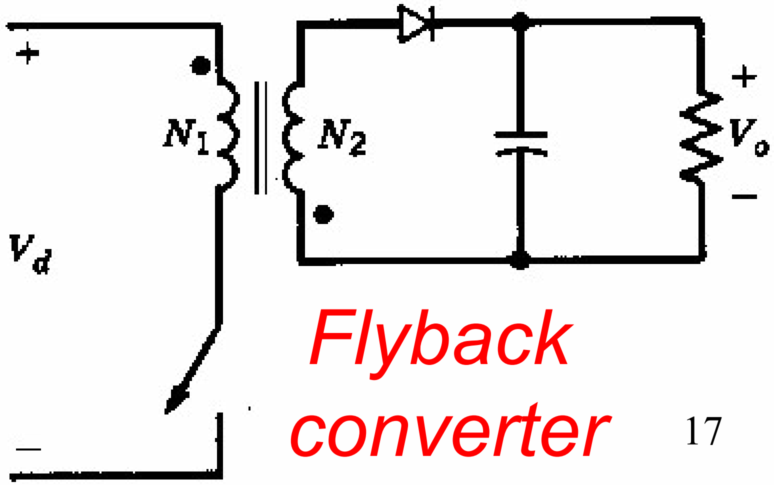
10.4.2 Flyback Converters（反激变换器）



Buck-boost converter

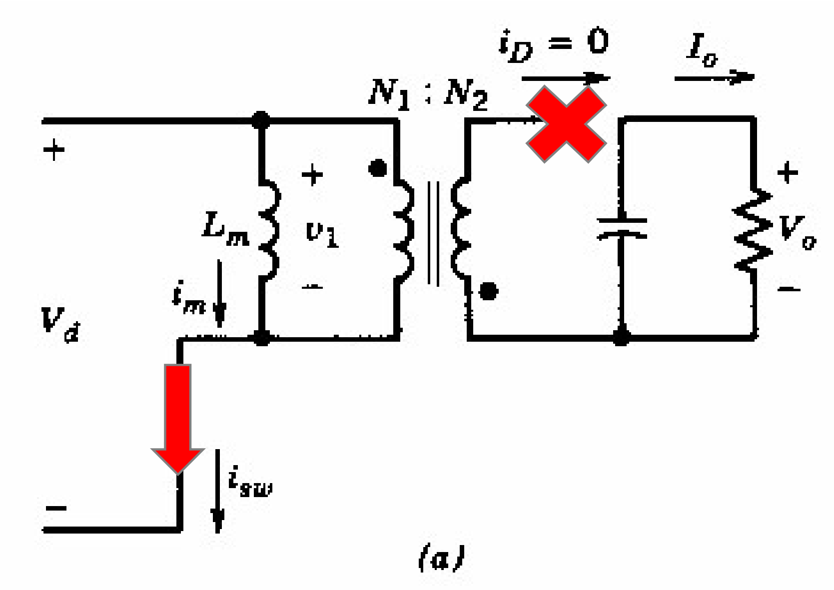


Redrawn topology



Flyback converter

The operation at switch on state



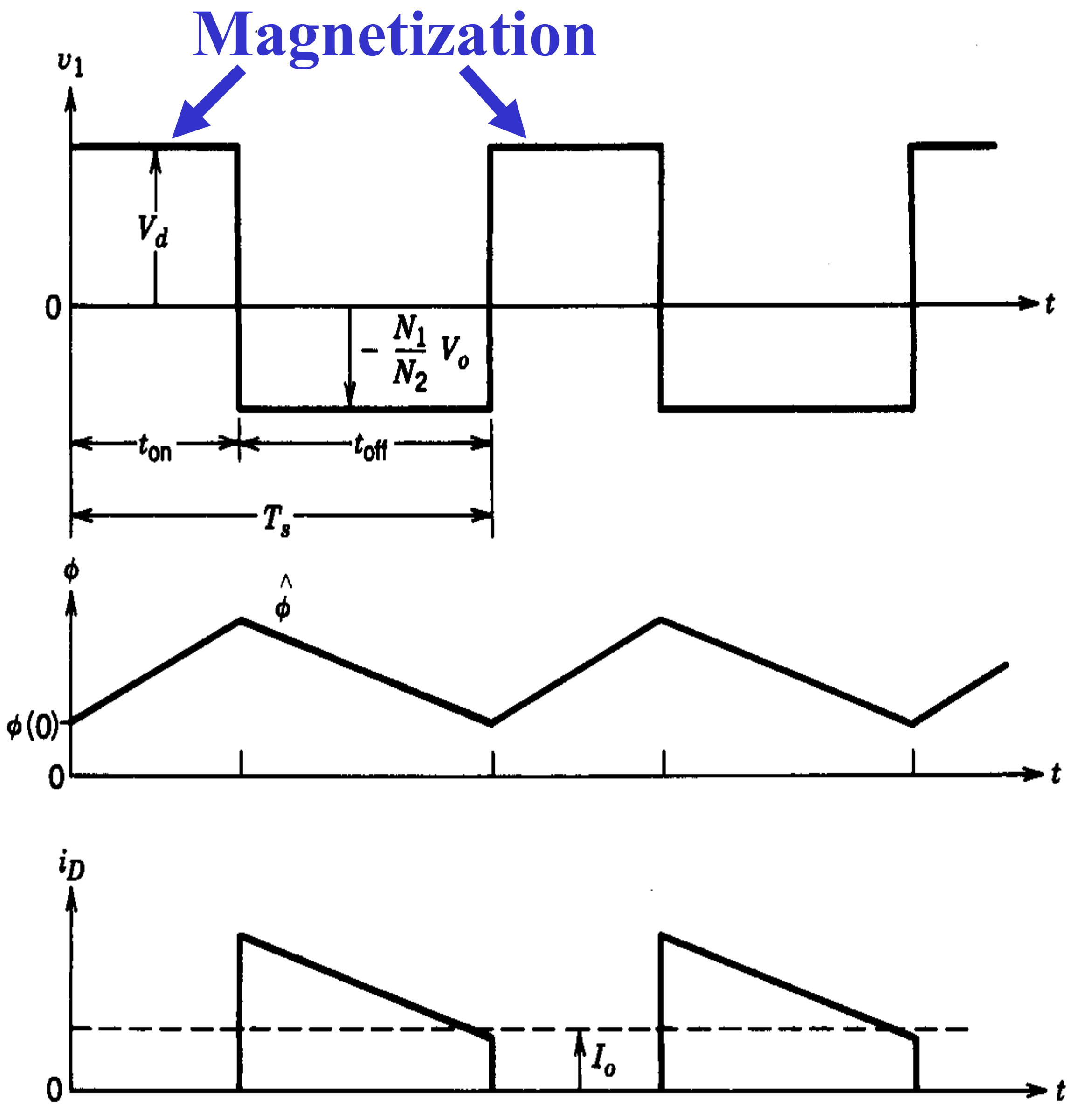


Figure 10-8 Flyback converter waveforms.

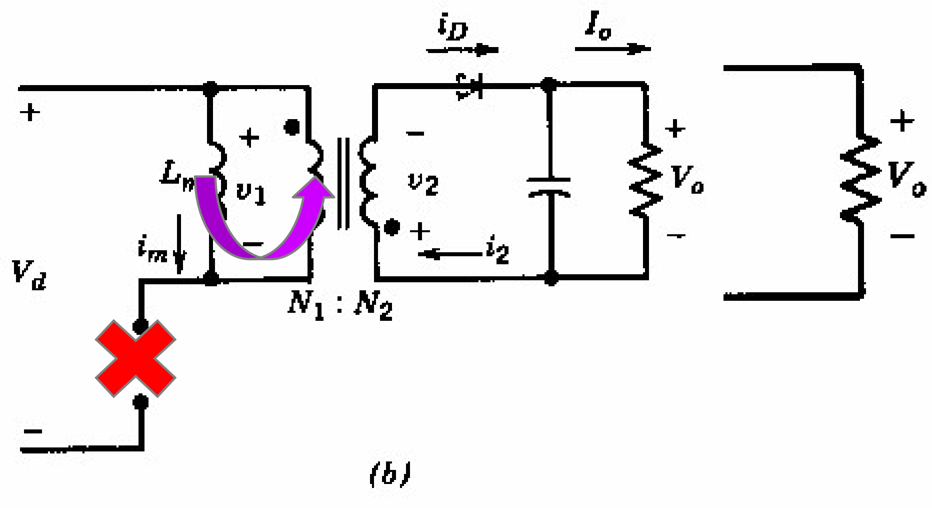
Inductor core flux

$$\phi(t) = \phi(0) + \frac{V_d}{N_1} t \qquad 0 < t < t_{on}$$

Peak flux

$$\hat{\phi} = \phi(t_{on}) = \phi(0) + \frac{V_d}{N_1} t_{on}$$

The operation at switch off state



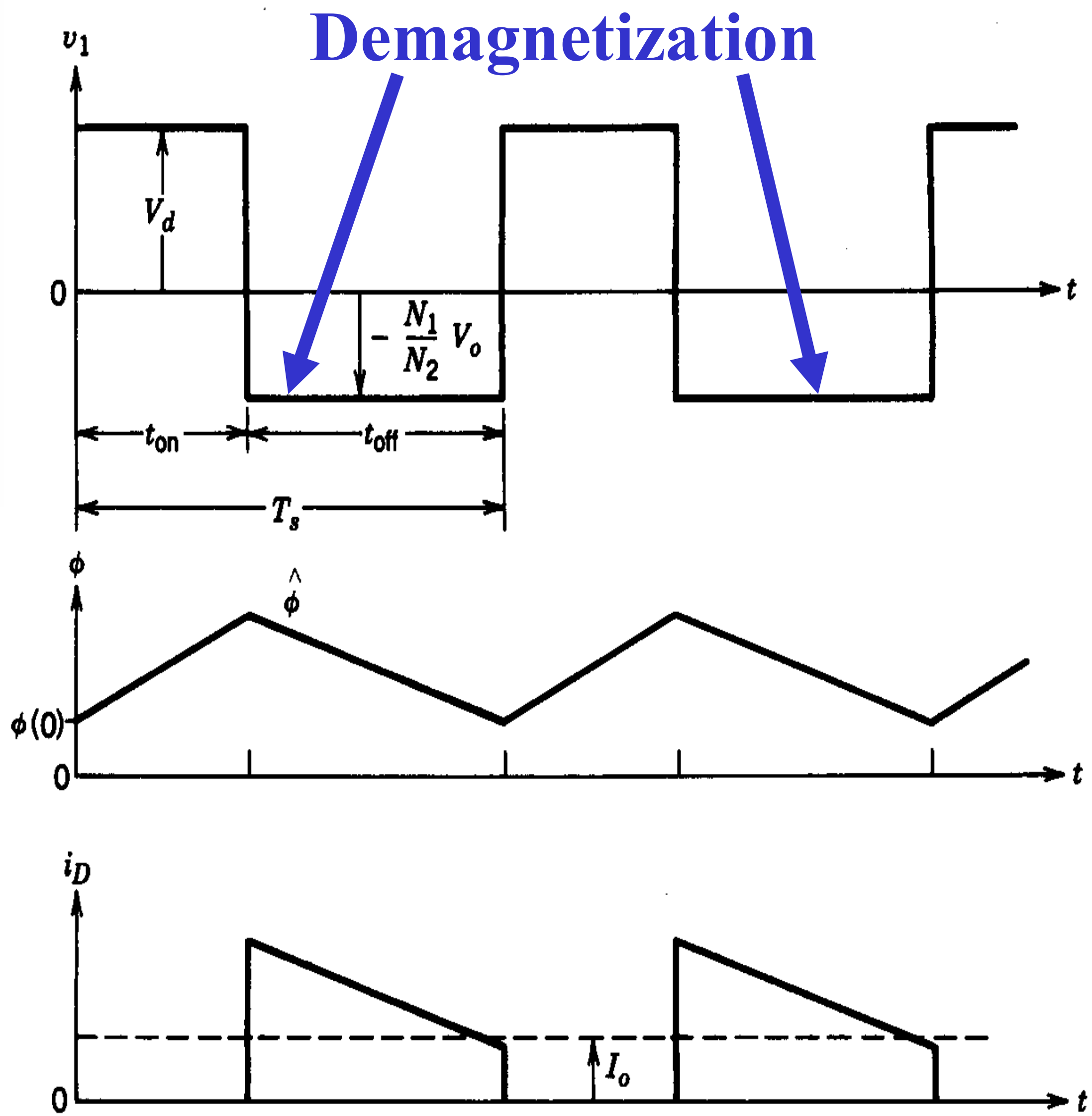


Figure 10-8 Flyback converter waveforms.

Inductor core flux

$$\phi(t) = \hat{\phi} - \frac{V_o}{N_2}(t - t_{on}), t_{on} < t < T$$

$$\phi(T_s) = \hat{\phi} - \frac{V_o}{N_2}(T_s - t_{on})$$

$$= \phi(0) + \frac{V_d}{N_1}t_{on} - \frac{V_o}{N_2}(T_s - t_{on})$$

10.4.2 Flyback Converters（反激变换器）

Voltage transfer ratio（电压传输比）

- Since the net change of flux through the core over one time period must be zero in steady state,

$$\phi(T_s) = \phi(0)$$

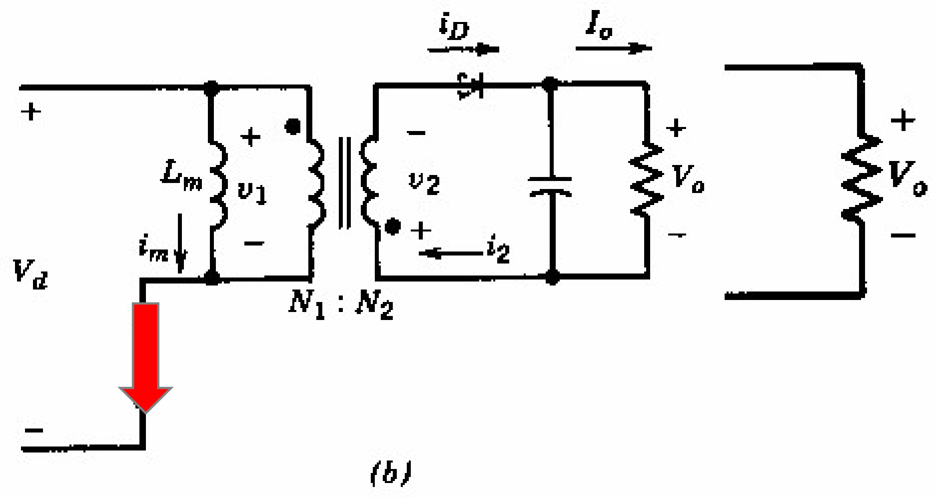
$$\Downarrow$$

$$\phi(T_s) = \phi(0) + \frac{V_d}{N_1} t_{on} - \frac{V_o}{N_2}(T_s - t_{on}) = \phi(0)$$

$$\frac{V_o}{V_d} = \frac{N_2}{N_1} \frac{D}{1-D} \qquad (D = t_{on}/T_s)$$

- This equation shows the voltage transfer ratio in a flyback converter depends on *D* in an identical manner as the buck-boost converter.

10.4.2 Flyback Converters（反激变换器）



Voltage and currents in a flyback converter

On interval

$$i_m(t) = i_{sw}(t) = I_m(0) + \frac{V_d}{L_m} t \ ,$$

$$(0 < t < t_{on})$$

$$\hat{I}_m = \hat{I}_{sw} = I_m(0) + \frac{V_d}{L_m} t_{on}$$

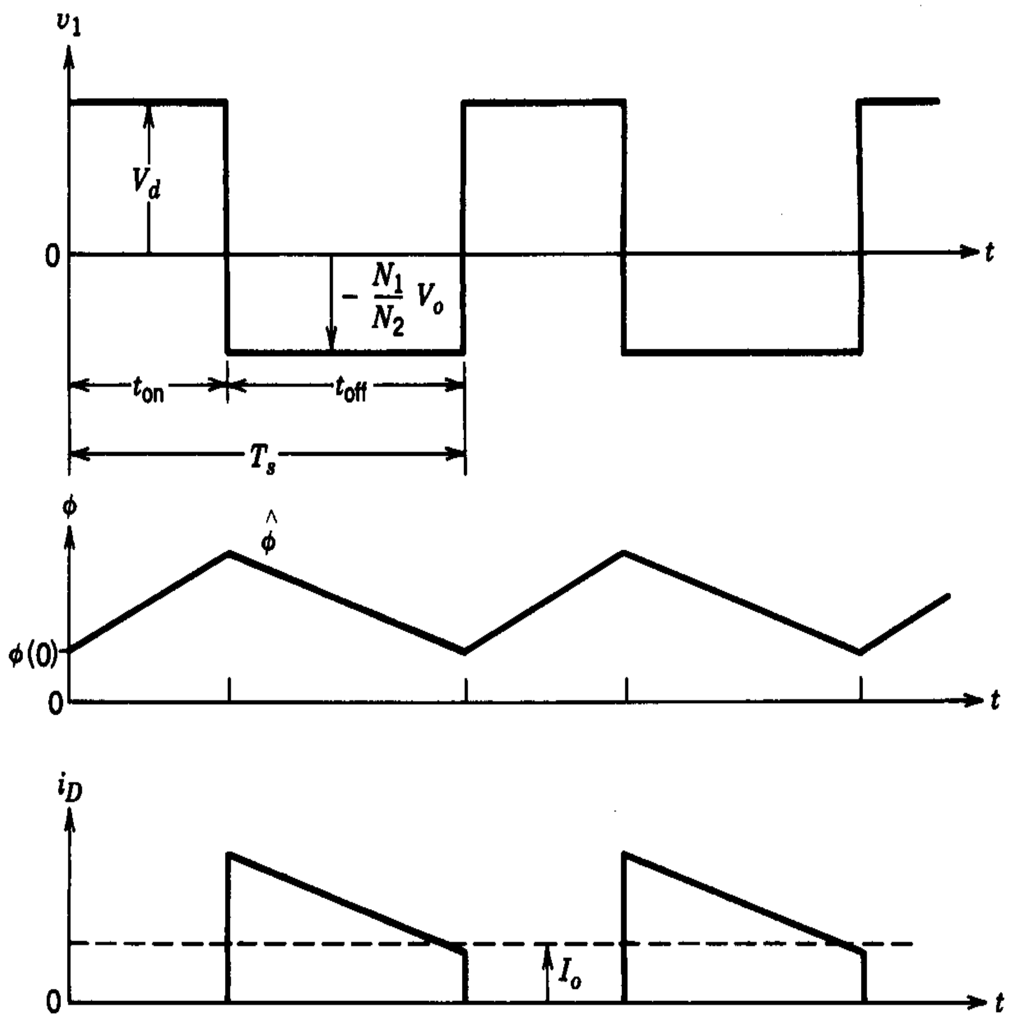
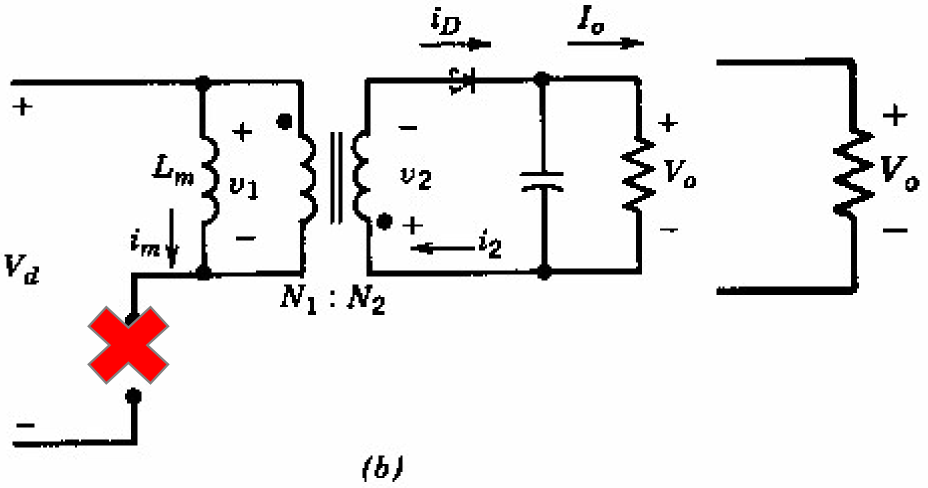


Figure 10-8 Flyback converter waveforms.

10.4.2 Flyback Converters（反激变换器）



Voltage and currents in a flyback converter

Off interval

$$i_m(t) = \hat{I}_m - \frac{V_o(N_1/N_2)}{L_m}(t - t_{on}),$$

$$(t_{on} < t < T_s)$$

$$i_D(t) = \frac{N_1}{N_2} i_m(t)$$

$$= \frac{N_1}{N_2}\left[\hat{I}_m - \frac{V_o(N_1/N_2)}{L_m}(t - t_{on})\right]$$

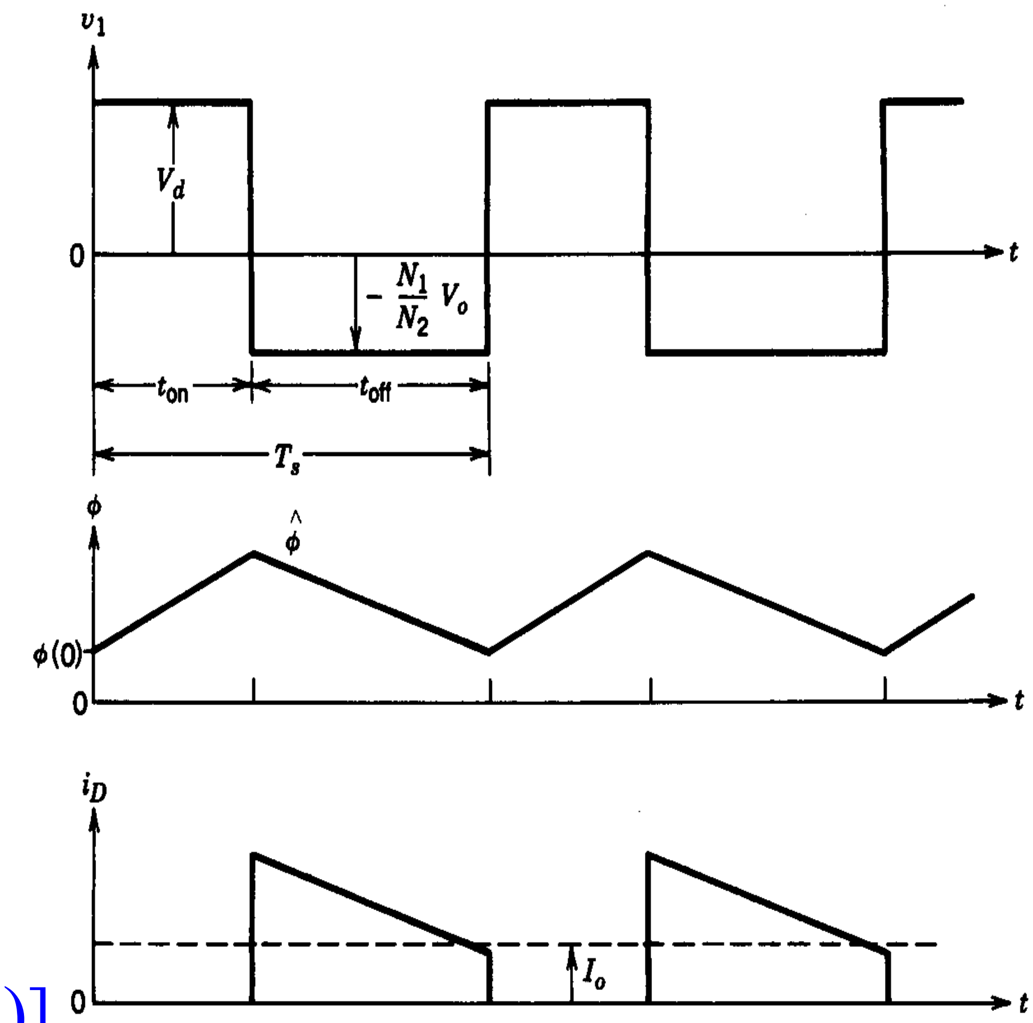
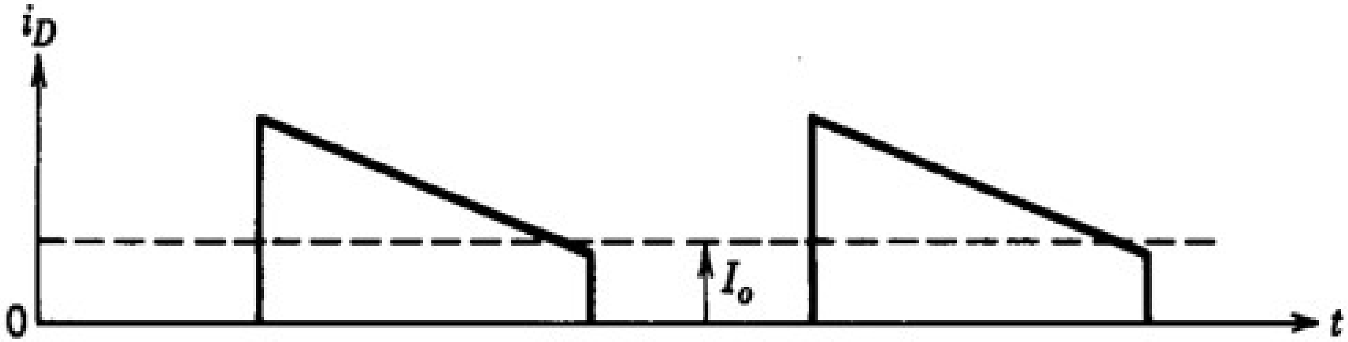


Figure 10-8 Flyback converter waveforms.

10.4.2 Flyback Converters（反激变换器）

Voltage and currents in a flyback converter

- Since the average diode current equals I_o ,



$$I_o = \frac{N_1}{N_2}[\hat{I}_m - \frac{1}{2}\frac{V_o(N_1/N_2)}{L_m}(T_s - t_{on})]\frac{T_s - t_{on}}{T_s}$$

$$\hat{I}_m = \hat{I}_{sw} = \frac{N_2}{N_1}\frac{1}{1-D}I_o + \frac{N_1}{N_2}\frac{(1-D)T_s}{2L_m}V_o$$

10.4.3 Forward Converters（正激变换器）

Idealized forward converter

On interval $$v_L = \frac{N_2}{N_1} V_d - V_o,\ 0 < t < t_{on}$$

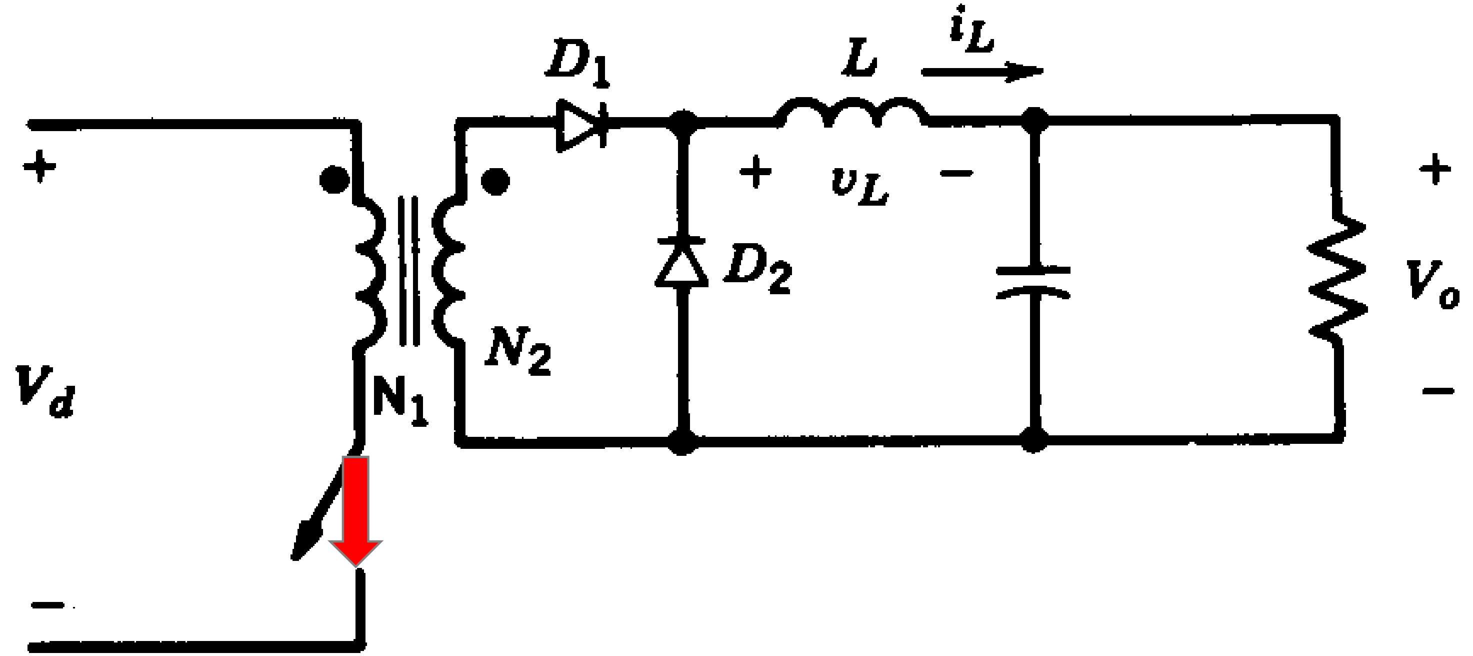


Figure 10-10 Idealized forward converter.

10.4.3 Forward Converters（正激变换器）

Idealized forward converter

Off interval $v_L = -V_o,\ t_{on} < t < T_s$

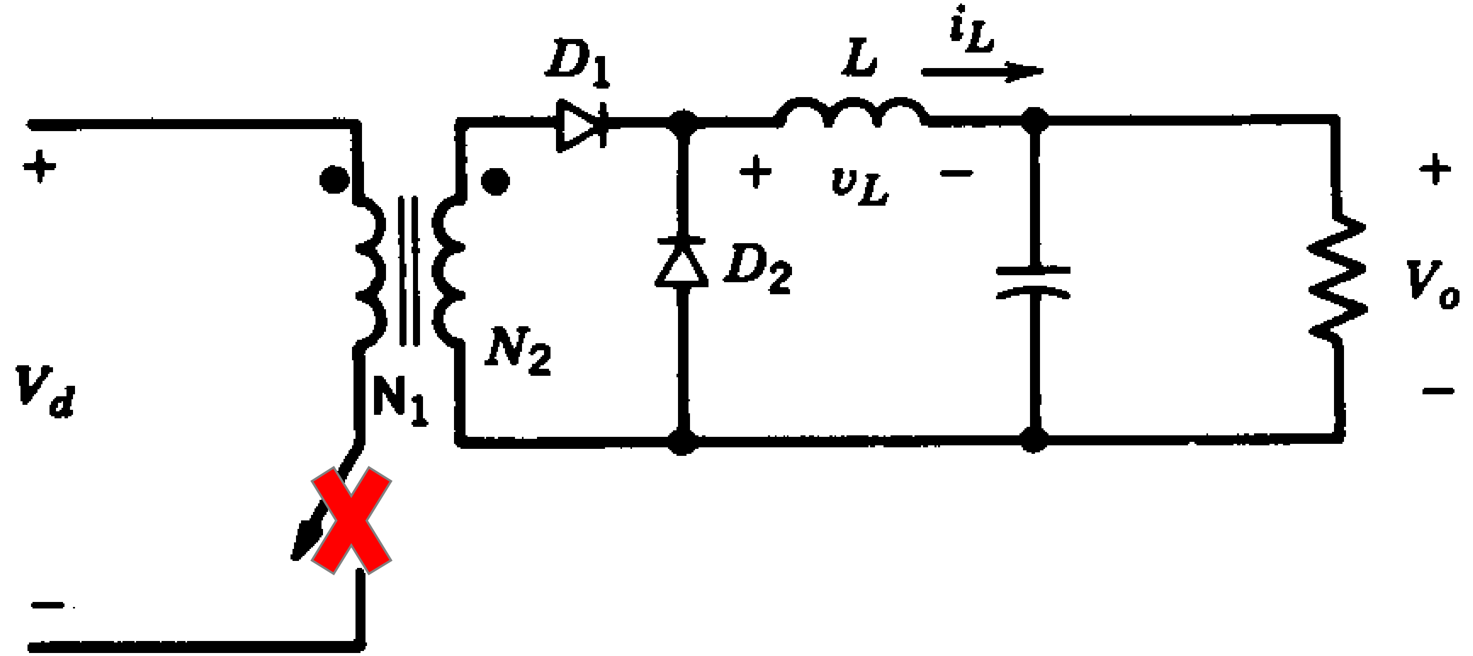


Figure 10-10 Idealized forward converter.

Idealized forward converter

Equating the integral of the inductor voltage over one time period to zero yields,

$$0 = \left(\frac{N_2}{N_1}V_d - V_o\right)\cdot t_{\text{on}} - V_o \cdot (T_s - t_{\text{on}}) \Rightarrow \frac{V_o}{V_d} = \frac{N_2}{N_1}D$$

$$(D = t_{\text{on}}/T_s)$$

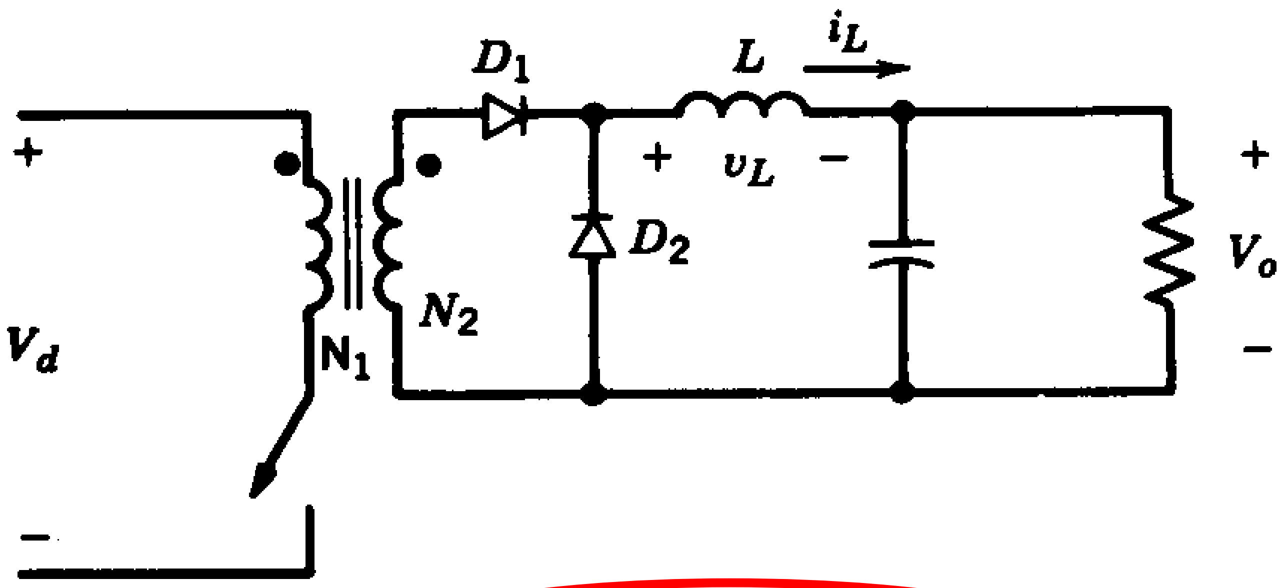


Figure 10-10 Idealized forward converter.

- The voltage transfer ratio is proportional to the switch duty ratio, similar to the step-down converter.

10.4.3 Forward Converters（正激变换器）

Idealized forward converter

Off interval $v_L = -V_o,\ t_{on} < t < T_s$

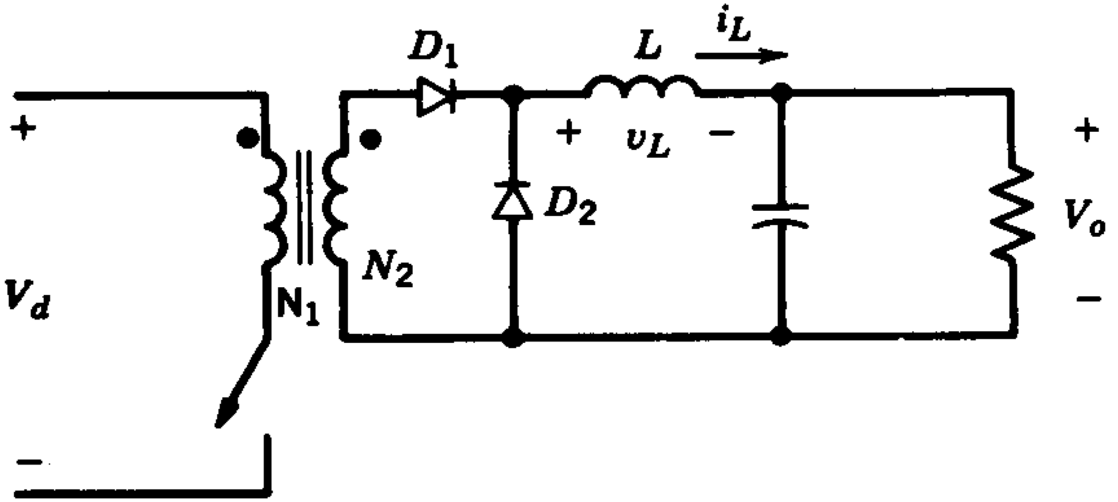
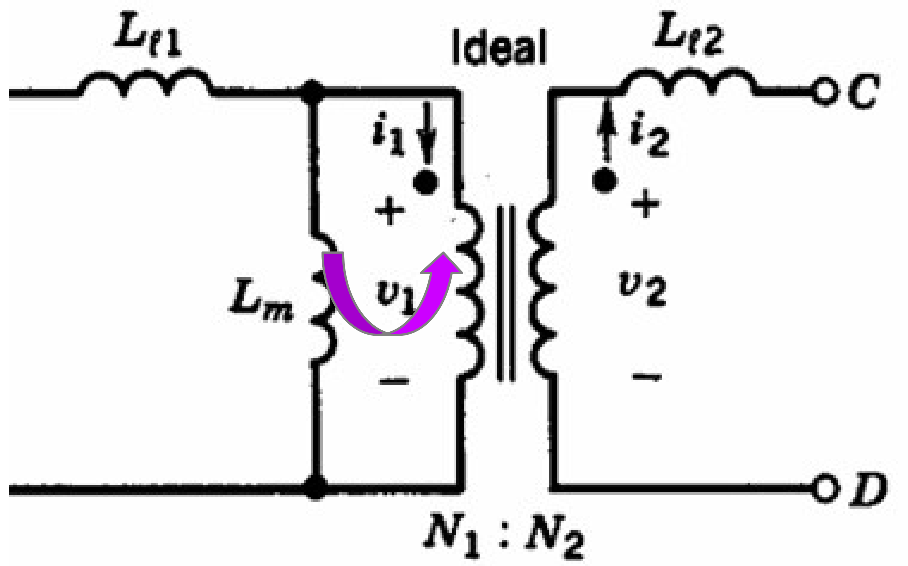


Figure 10-10 Idealized forward converter.

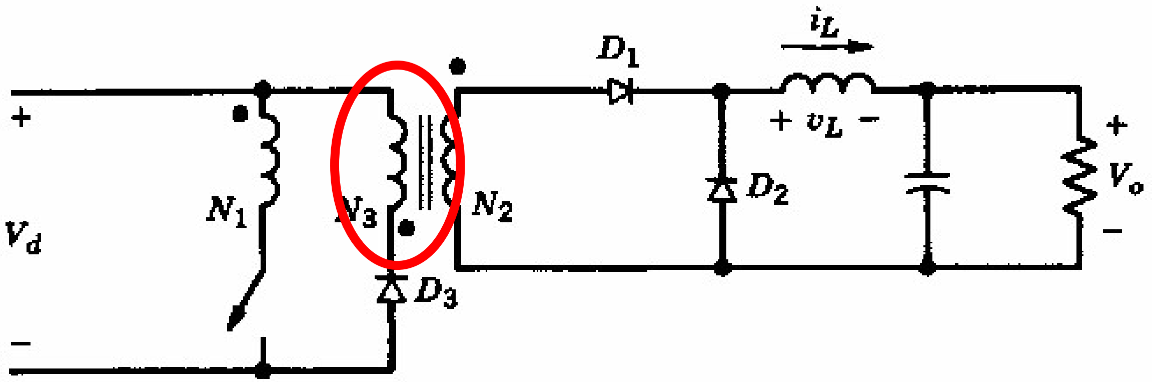


No freewheeling currents flow through D_1

Practical forward converter

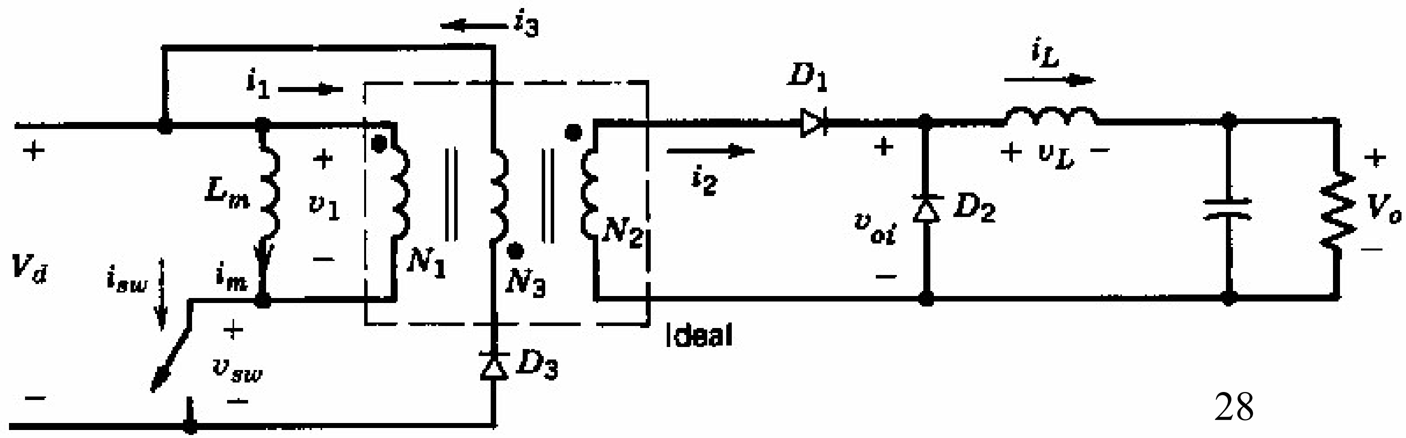
- In a practical forward converter, the transformer magnetizing current must be taken into account for a proper operation. A third demagnetizing winding is used to allow the transformer magnetic energy to be recovered.

Practical forward converter topology

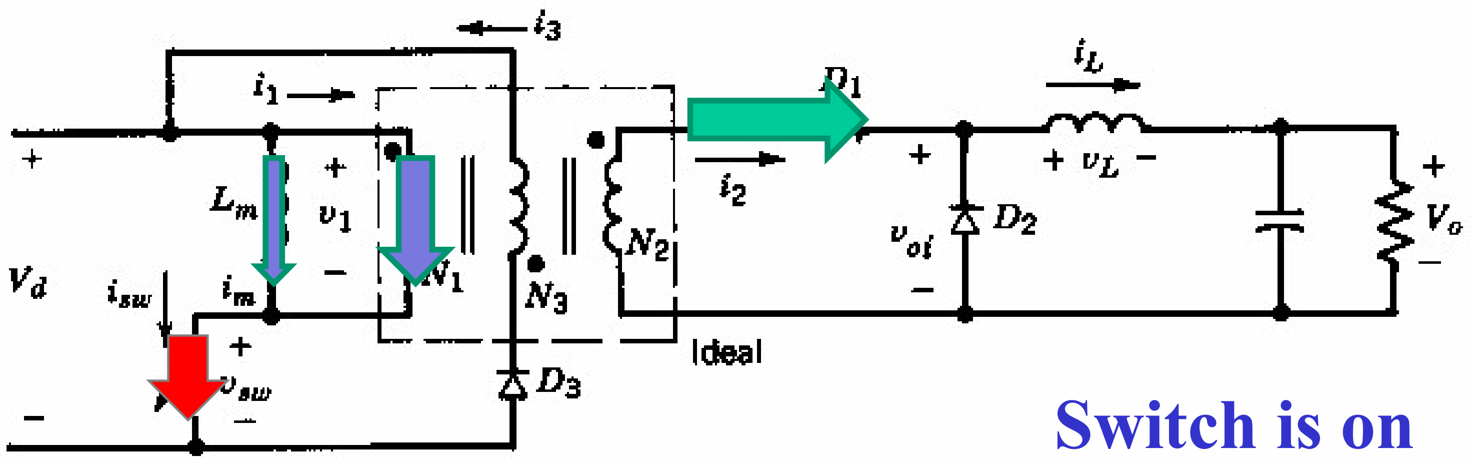


(a)

Equivalent circuit



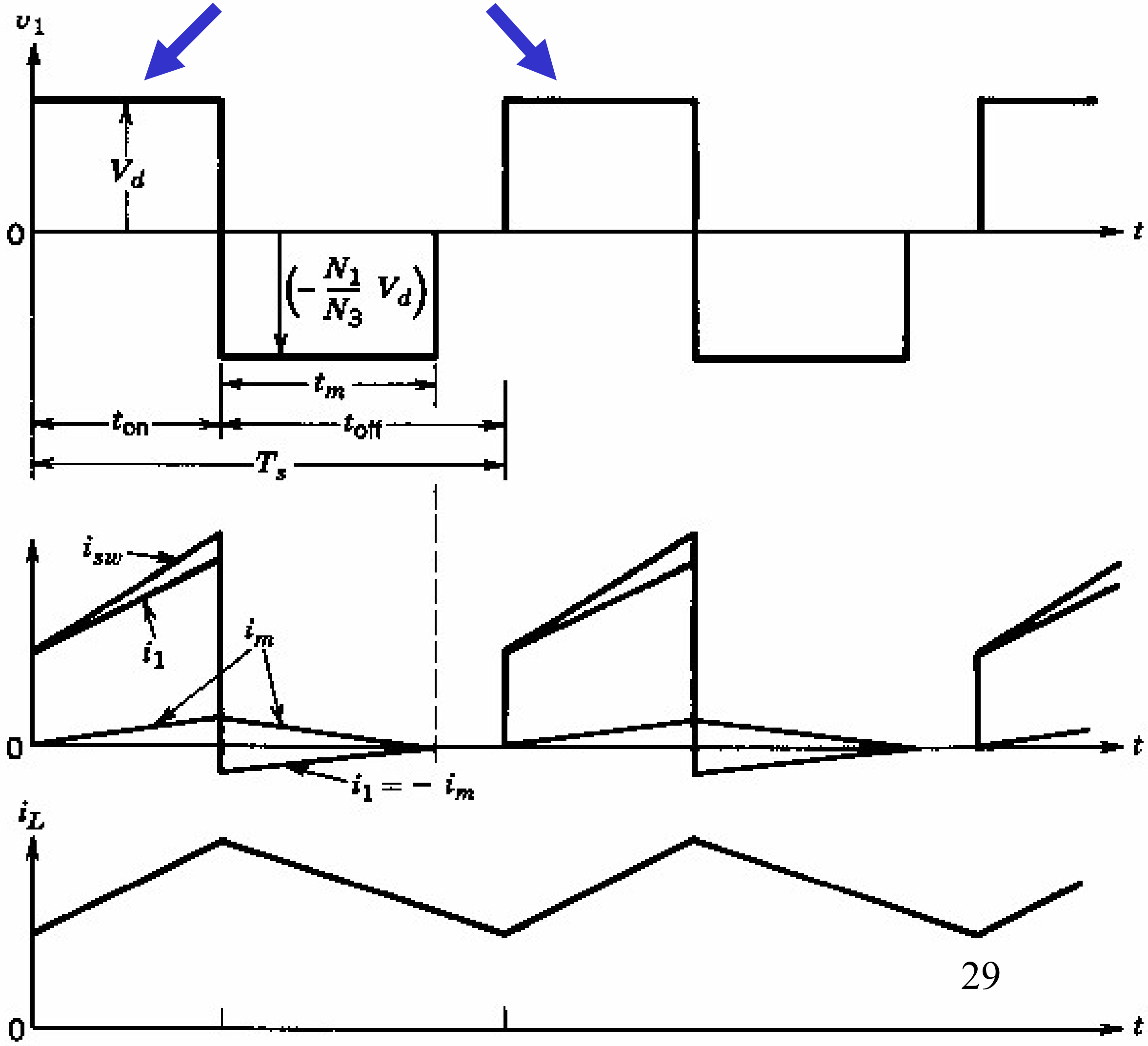
(b)

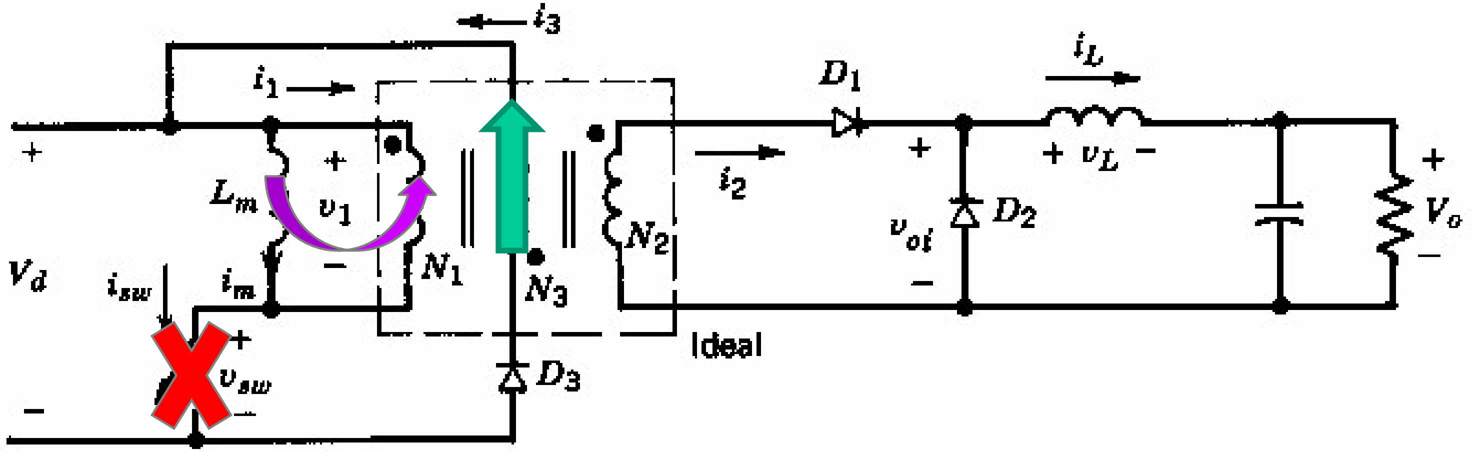


Switch is on

$$v_1 = V_d \qquad 0 < t < t_{on}$$

Switch is on





Switch is on

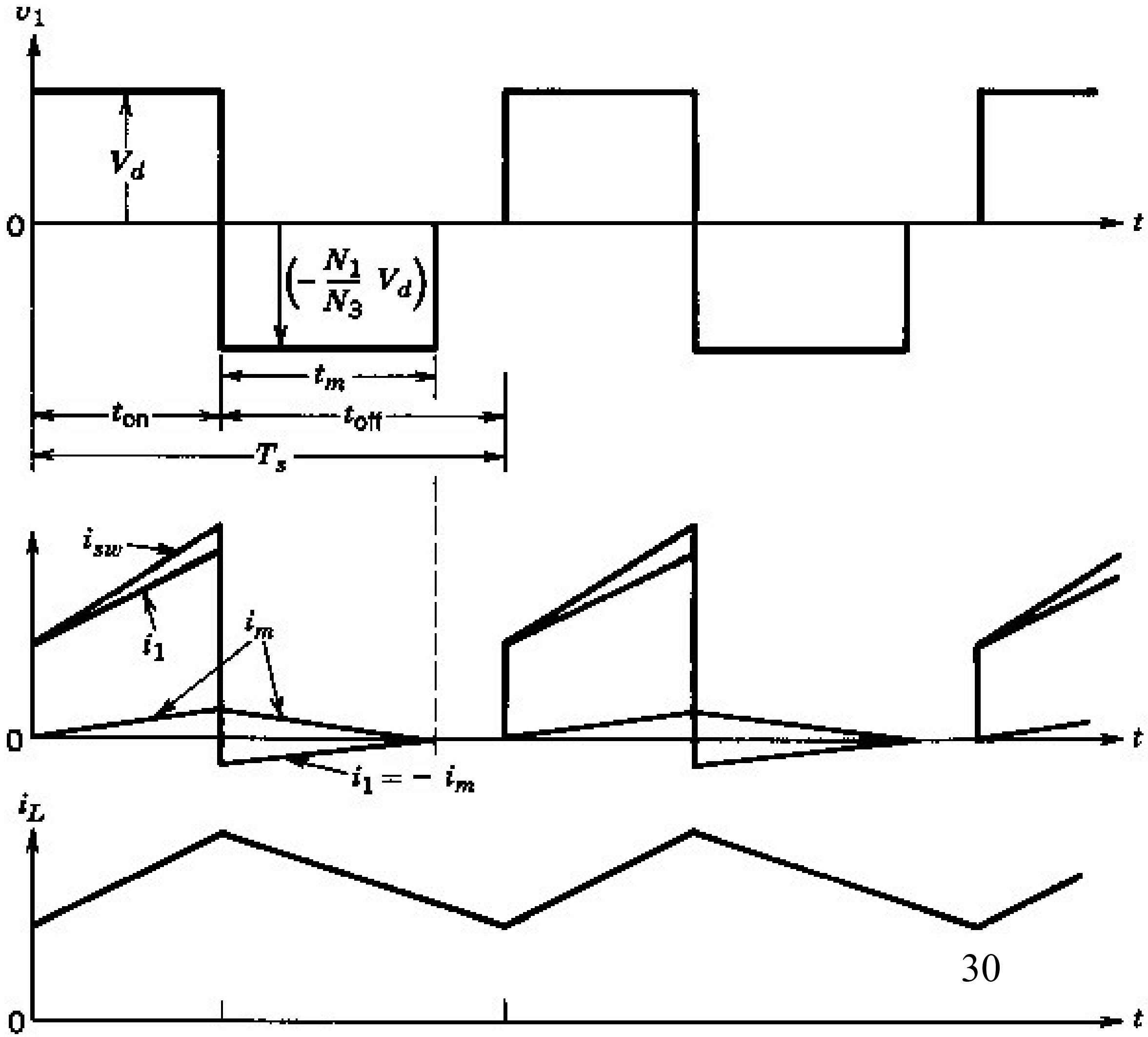
$$v_1 = V_d \qquad 0 < t < t_{on}$$

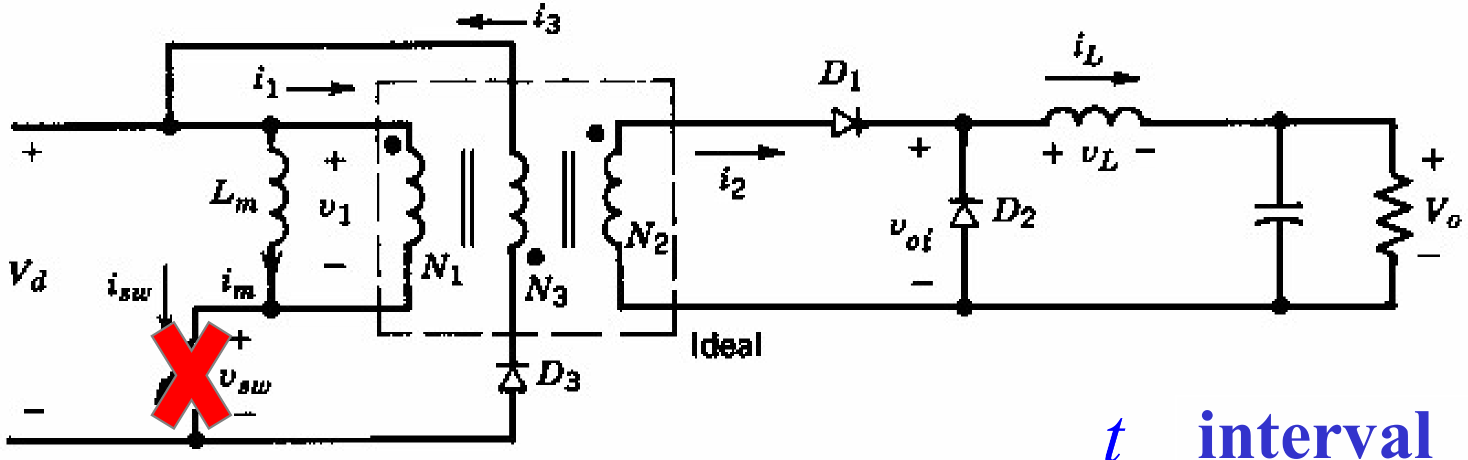
Switch is off

$$i_2 = 0$$

$$i_1 = -i_m \qquad N_1 i_1 = -N_3 i_3$$

$$i_3 = \frac{N_1}{N_3} i_m$$





Switch is on

$$v_1 = V_d \qquad 0 < t < t_{on}$$

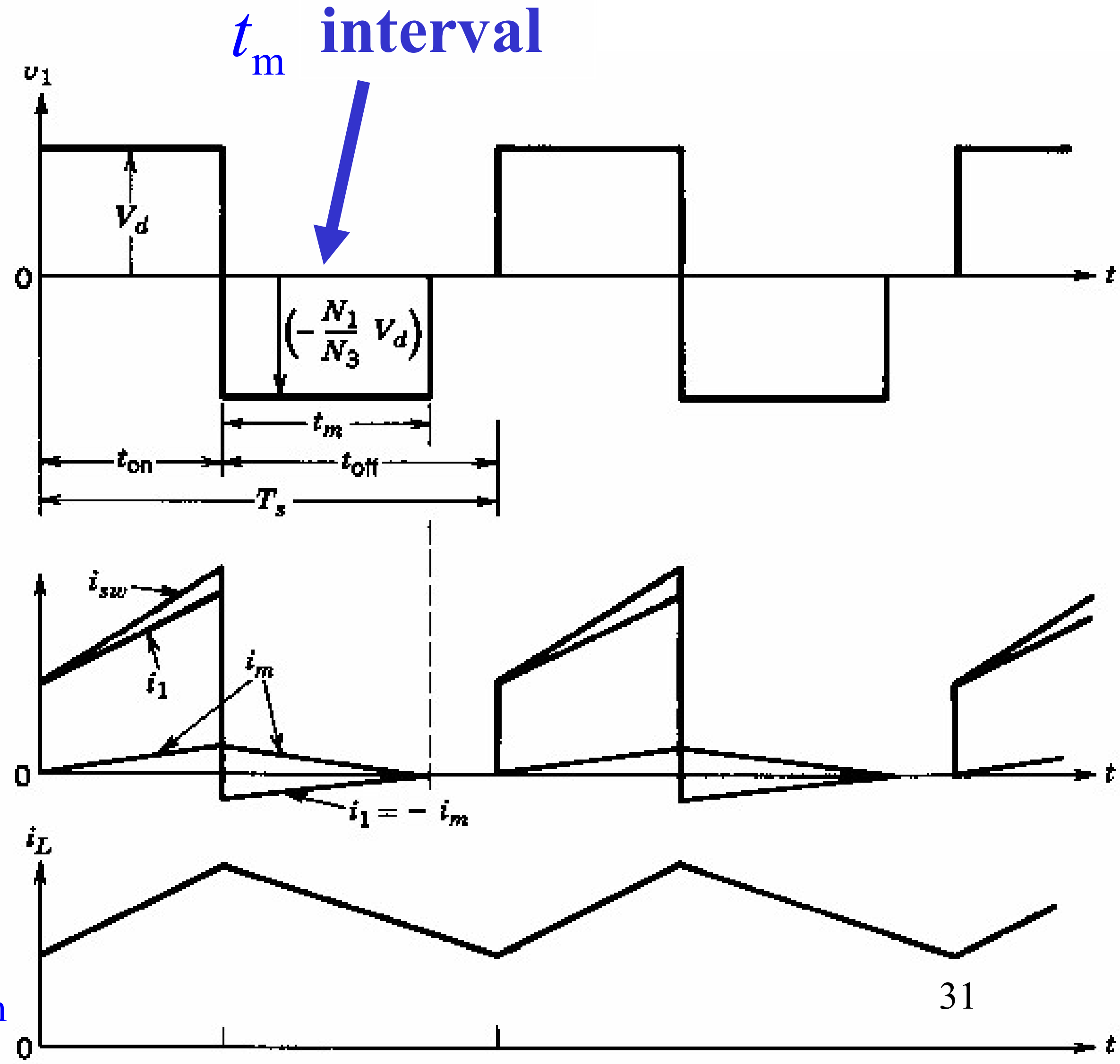
Switch is off

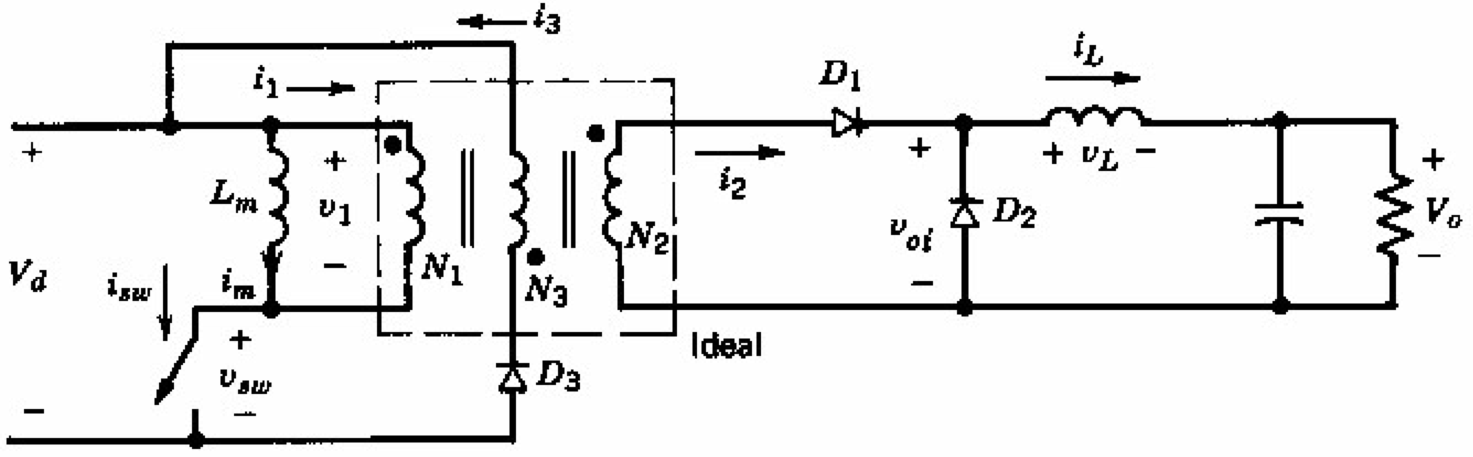
$$i_1 = -i_m \qquad N_1 i_1 = -N_3 i_3$$

$$i_3 = \frac{N_1}{N_3} i_m$$

t_m interval

$$v_1 = -\frac{N_1}{N_3} V_d \quad t_{on} < t < t_{on} + t_m$$

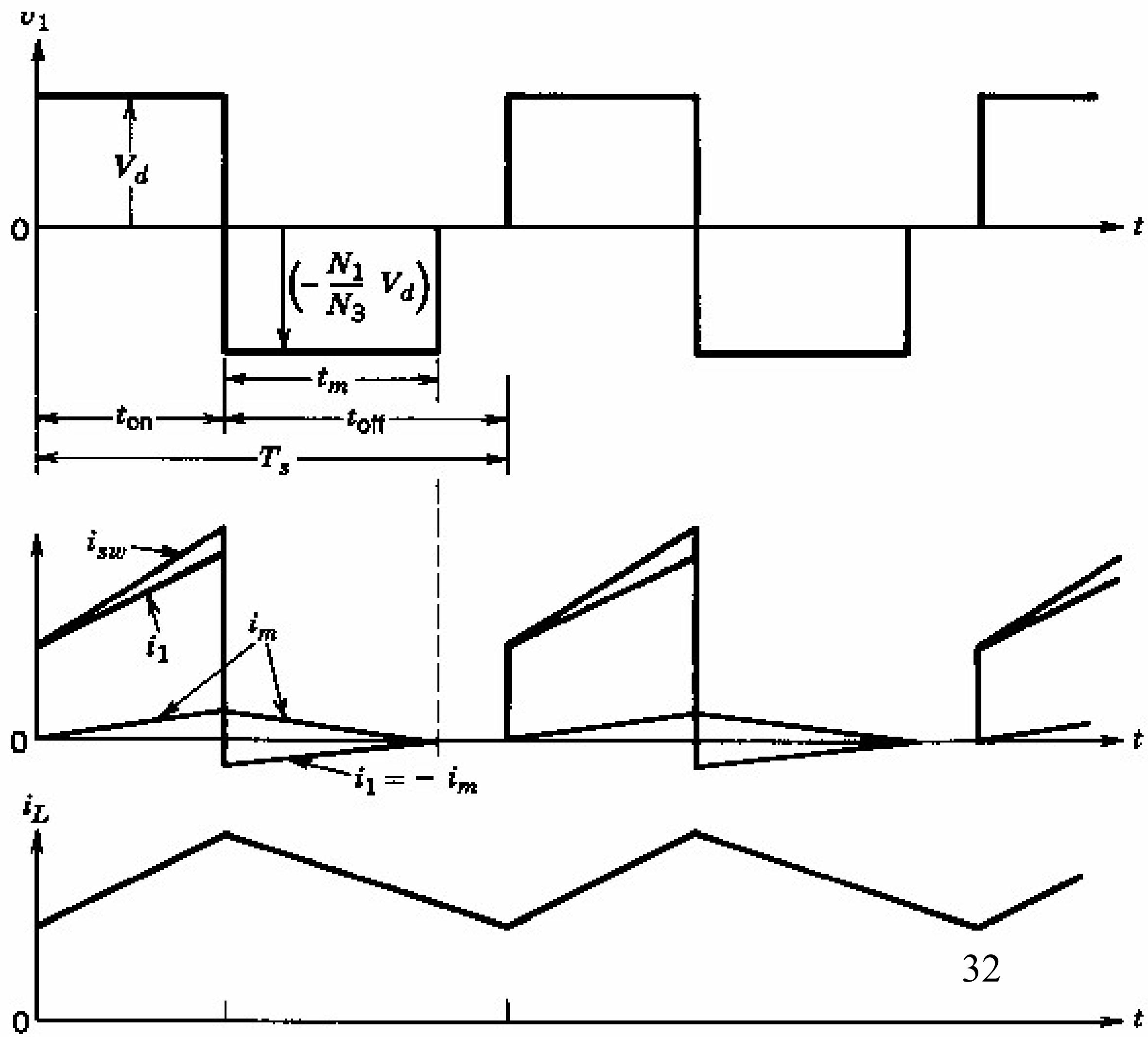


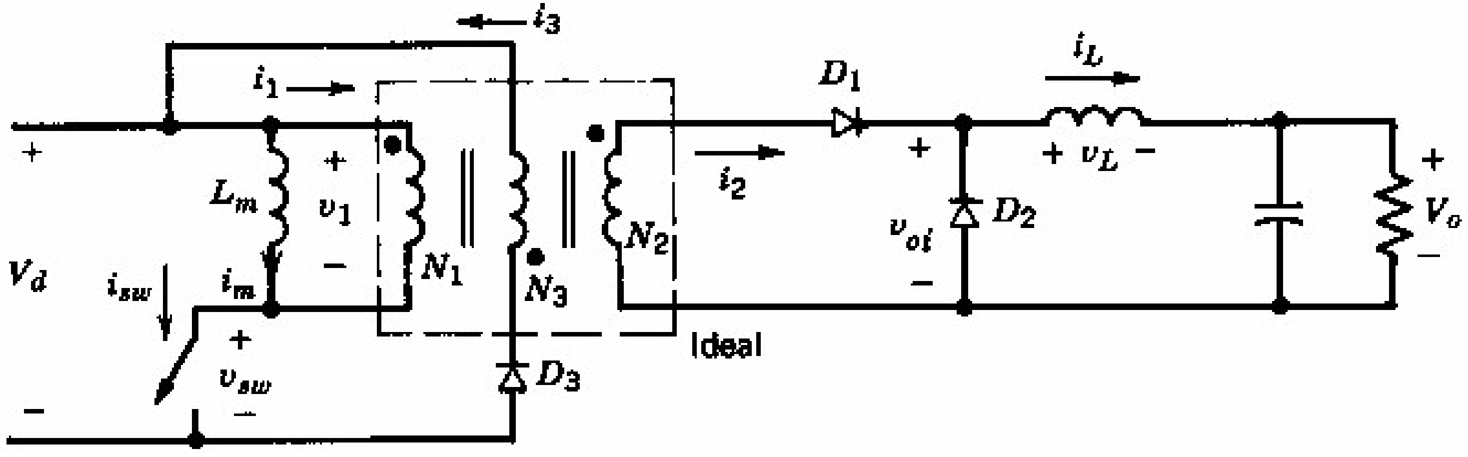


t_{m} can be obtained by recognizing that the time integral of v_1 across L_{m} must be zero over one time period.

$$V_d \cdot t_{\mathrm{on}} - \frac{N_1}{N_3} V_d \cdot t_m = 0$$

$$\frac{t_{\mathrm{m}}}{T_{\mathrm{s}}} = \frac{N_3}{N_1} D \quad (D = t_{\mathrm{on}} / T_s)$$



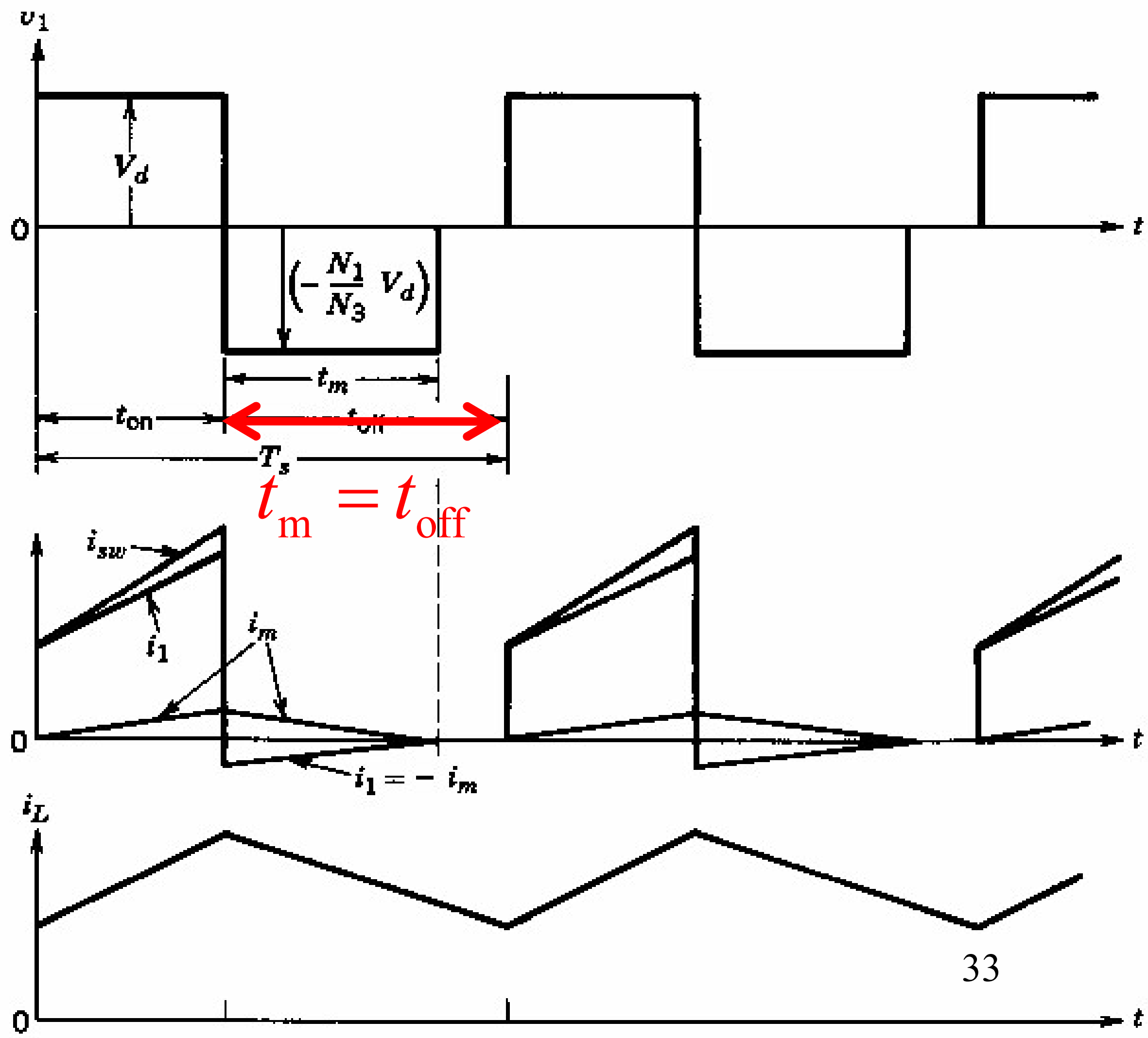


t_m can be obtained by recognizing that the time integral of v_1 across L_m must be zero over one time period.

$$\frac{t_m}{T_s} = \frac{N_3}{N_1} D \quad (D = t_{on}/T_s)$$

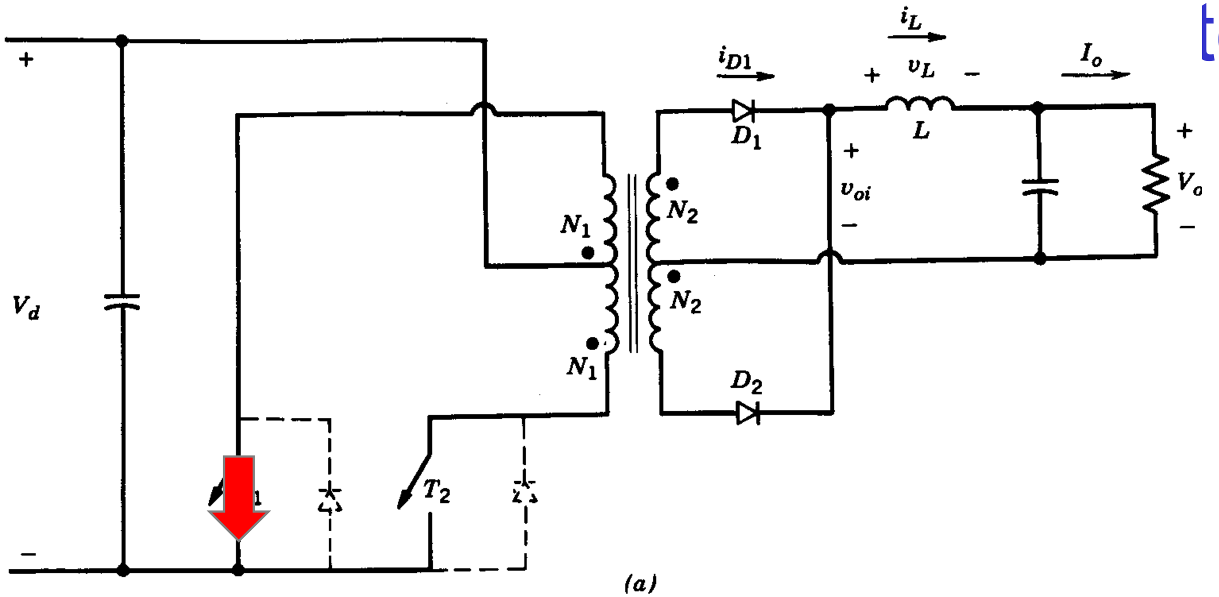
The maximum duty ratio is,

$$(1 - D_{max}) = \frac{N_3}{N_1} D_{max}$$



— dc-dc Converters with Electrical Isolation —

ter（推挽变换器）



T_1 is on

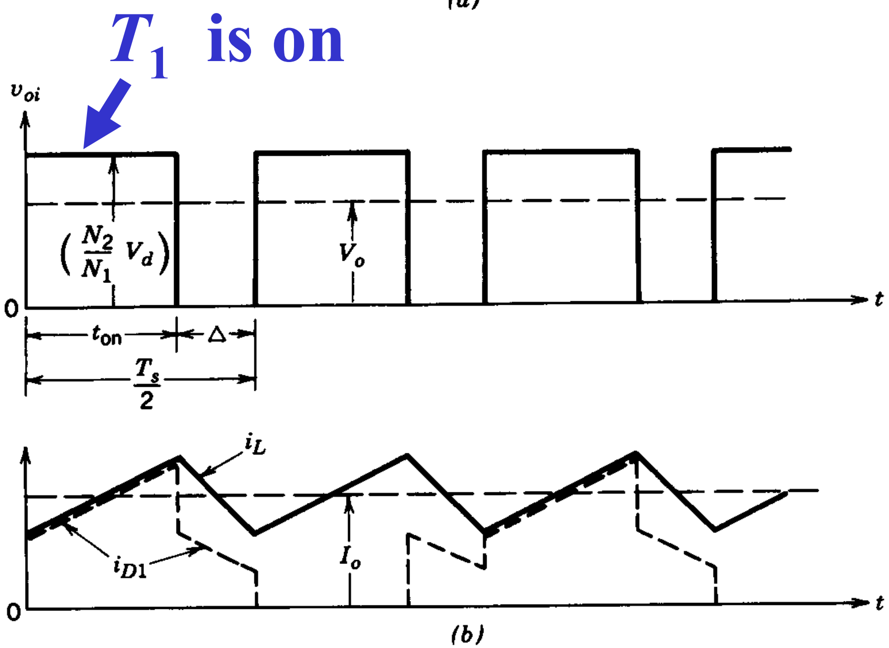


Figure 10-13 Push–pull converter.

T_1 is on

$$v_{oi} = \frac{N_2}{N_1} V_d$$

$$v_L = \frac{N_2}{N_1} V_d - V_o \quad 0 < t < t_{on}$$

— dc-dc Converters with Electrical Isolation —

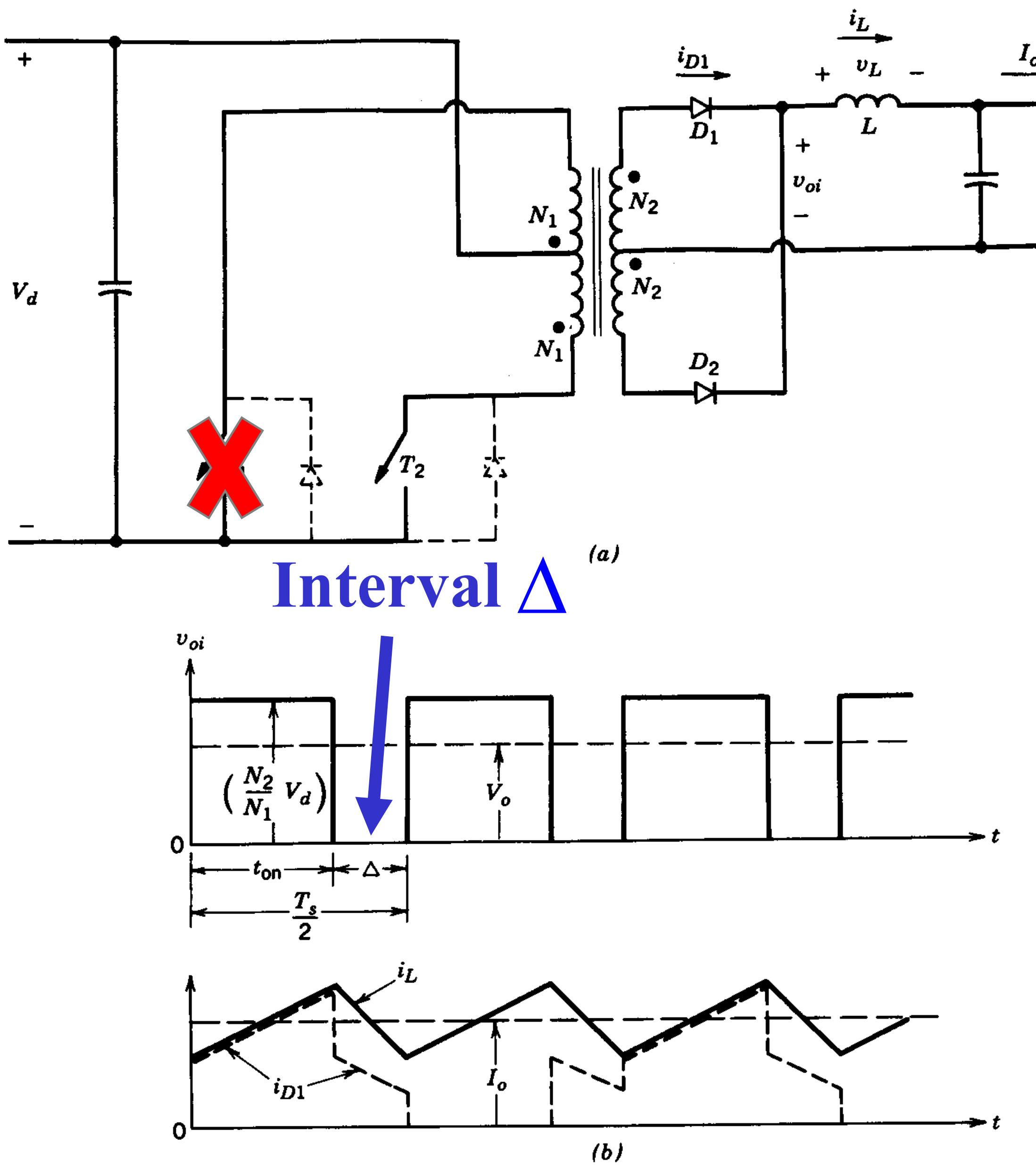


Figure 10-13 Push–pull converter.

T_1 is on

$$v_{oi} = \frac{N_2}{N_1}V_d$$

$$v_L = \frac{N_2}{N_1}V_d - V_o \quad 0 < t < t_{on}$$

Interval Δ

$$v_{oi} = 0$$

$$v_L = -V_o \quad t_{on} < t < t_{on} + \Delta$$

$$i_{D1} \approx i_{D2} \approx \frac{1}{2}i_L$$

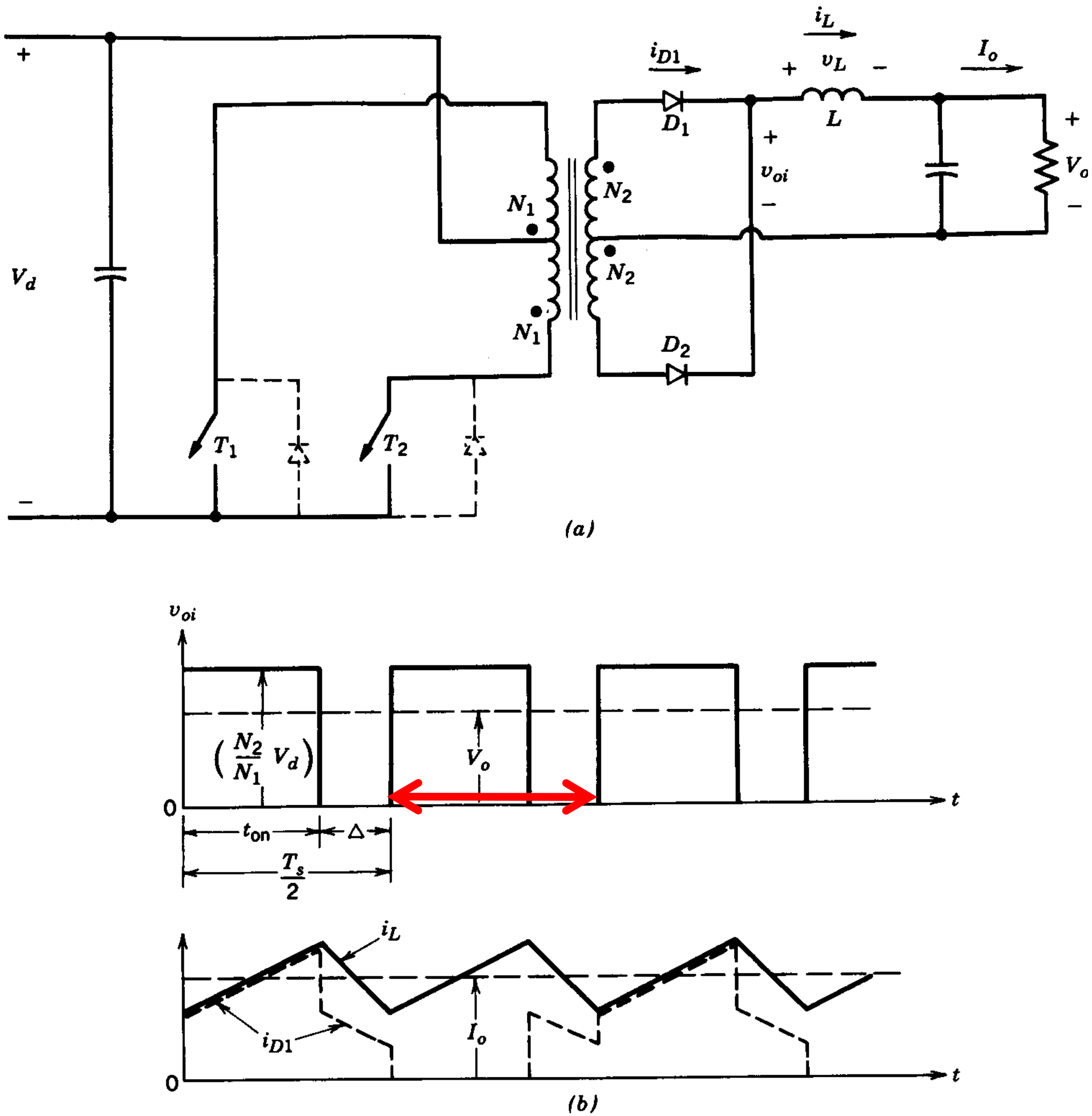


Figure 10-13 Push–pull converter.

10.4.4 Push-Pull Converter（推挽变换器）

- The waveforms of the next half-cycle repeat with a period $T_s/2$, which consists of t_{on} (T_2 is on) and the interval Δ;

$$t_{on} + \Delta = \frac{1}{2} T_s$$

— dc-dc Converters with Electrical Isolation —

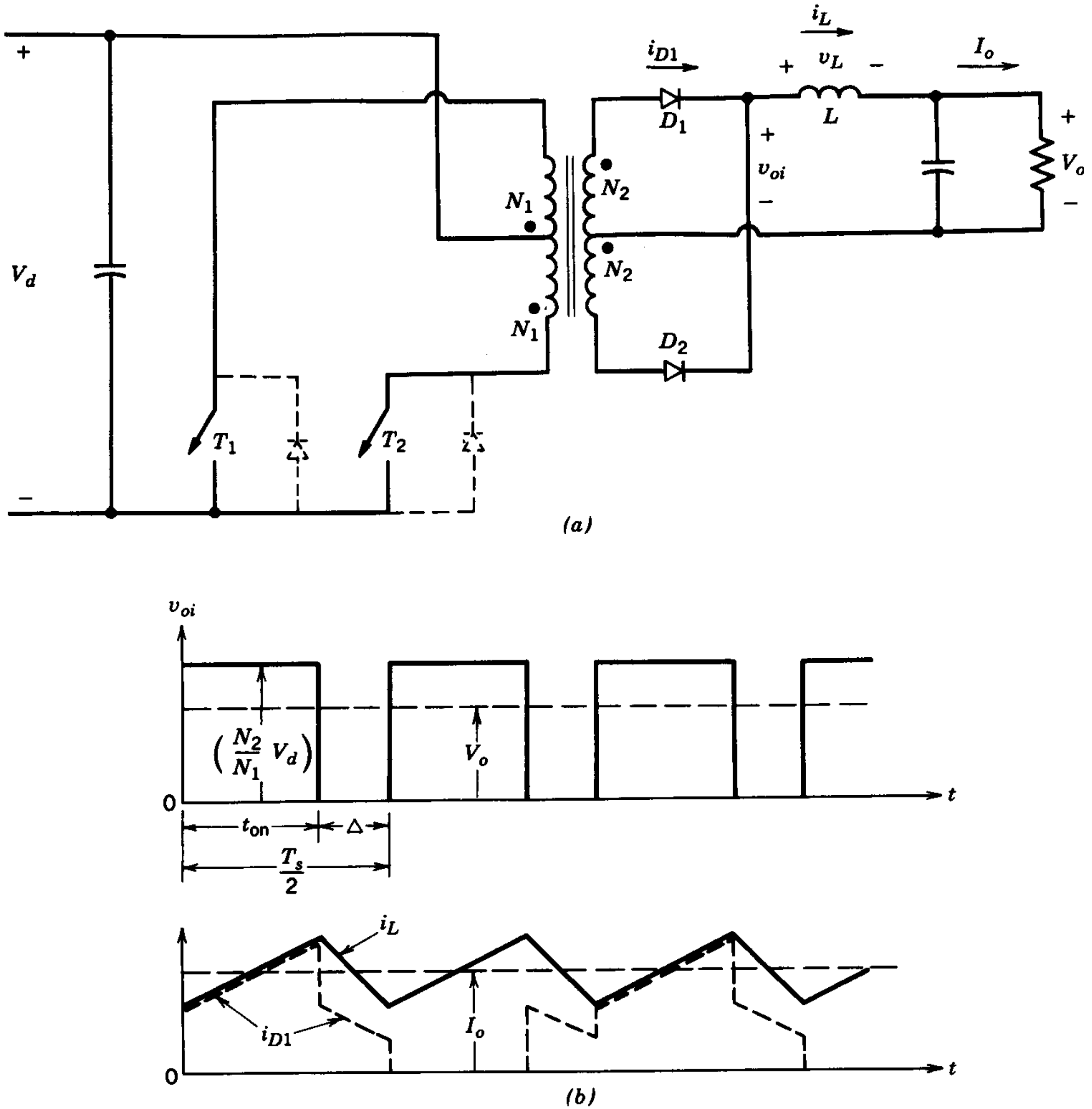


Figure 10-13 Push–pull converter.

- Equating the time integral of the inductor voltage during $T_s/2$ to zero yields,

$$v_L = \frac{N_2}{N_1}V_d - V_o \quad 0 < t < t_{on}$$

$$v_L = -V_o \quad t_{on} < t < t_{on} + \Delta$$

$$t_{on} + \Delta = \frac{1}{2}T_s$$

主观题 10分

设置

Please derive the voltage transfer ratio of the push-pull converter.

作答

— dc-dc Converters with Electrical Isolation —

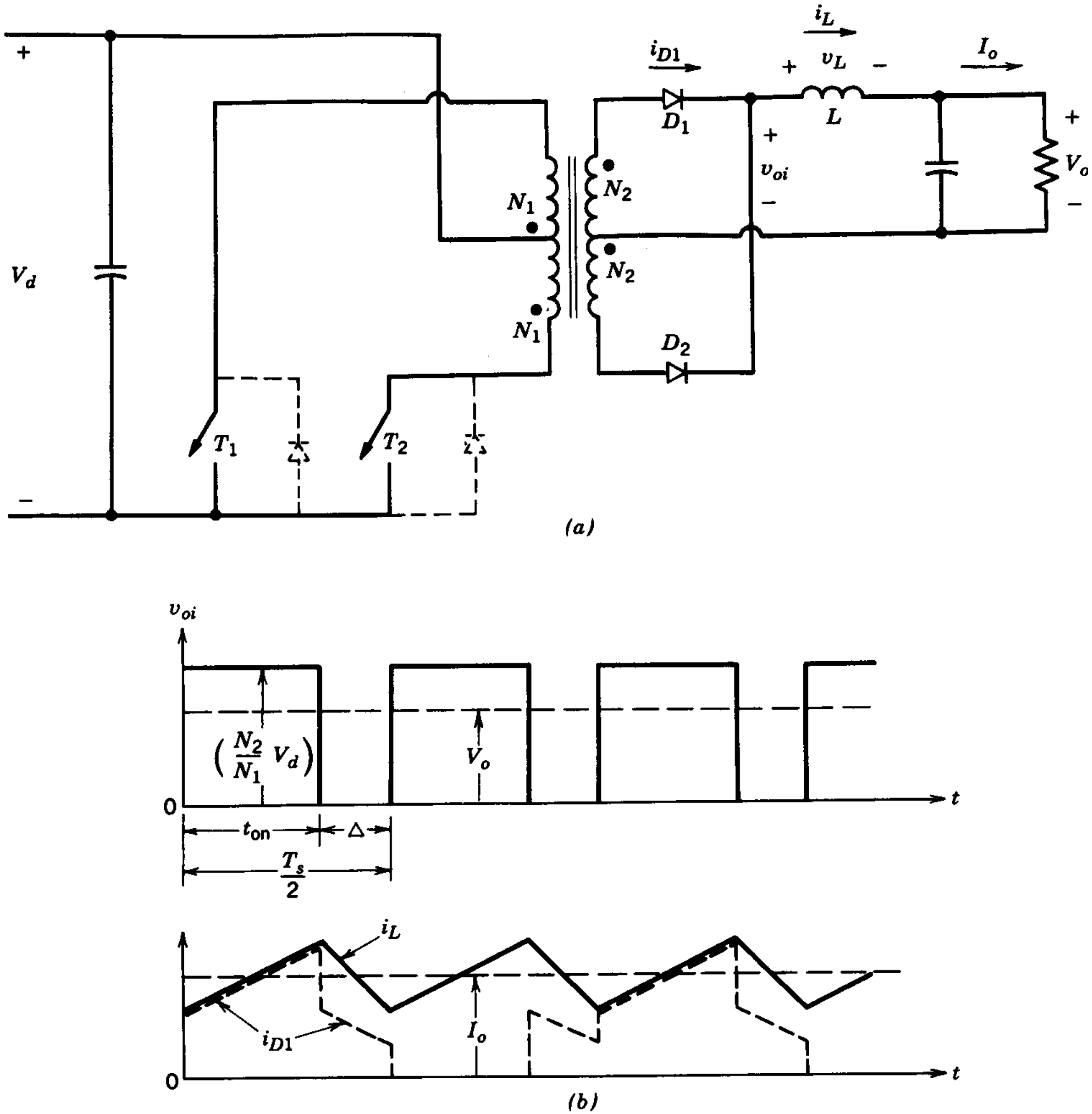


Figure 10-13 Push–pull converter.

- Equating the time integral of the inductor voltage during $T_s/2$ to zero yields,

$$v_L = \frac{N_2}{N_1}V_d - V_o \quad 0 < t < t_{on}$$

$$v_L = -V_o \quad t_{on} < t < t_{on} + \Delta$$

$$t_{on} + \Delta = \frac{1}{2}T_s$$

$$\frac{V_o}{V_d} = 2\frac{N_2}{N_1}D \quad 0 < D < 0.5$$

$$D = t_{on}/T_s$$

Chap.10 Switching dc Power Supply

— dc-dc Converters with Electrical Isolation —

erter（半桥变换器）

T_1 is on

$$v_{oi} = (N_2/N_1)(V_d/2)$$

$$v_L = \frac{N_2}{N_1}\frac{V_d}{2} - V_o \quad 0 < t < t_{on}$$

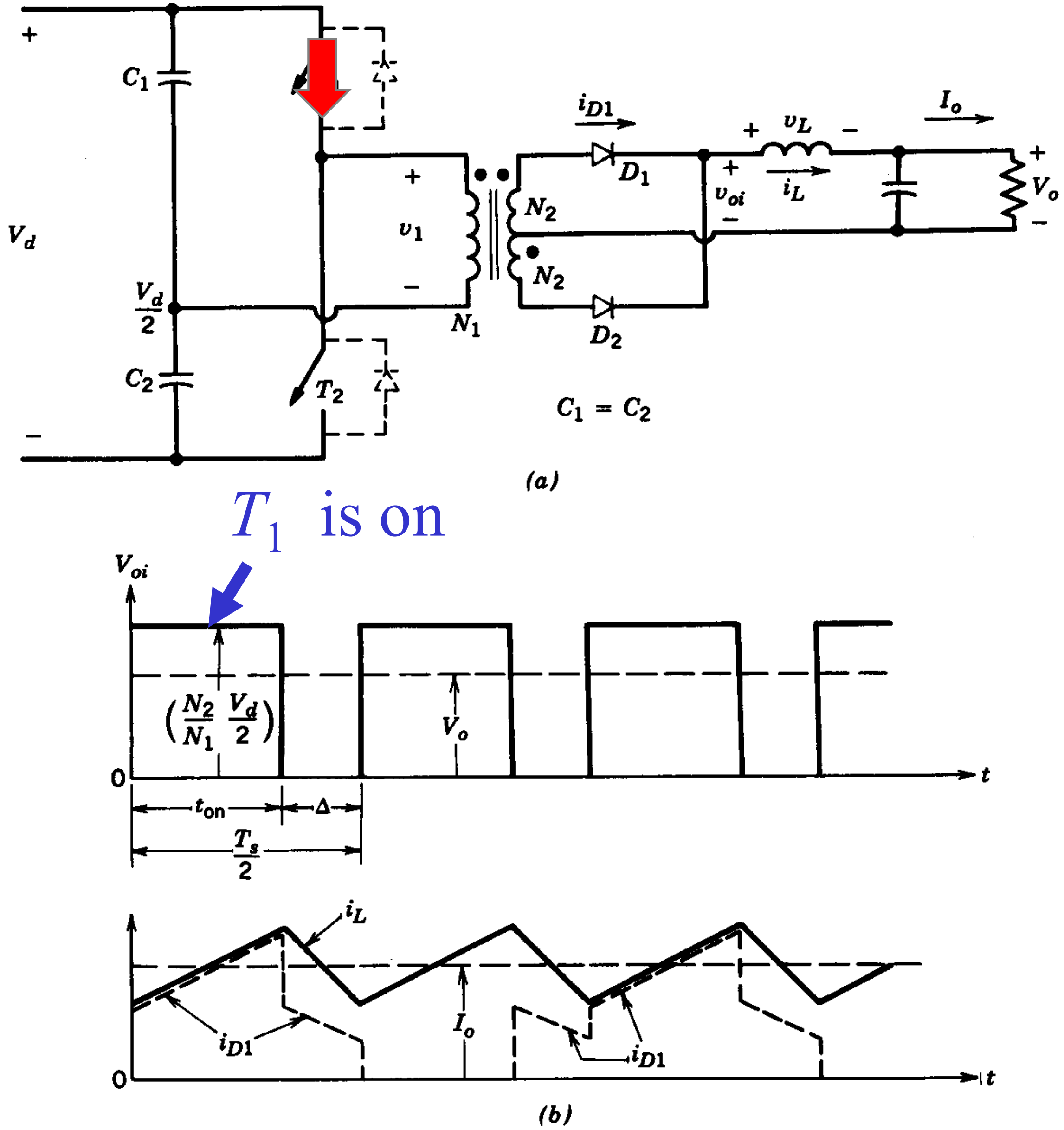


Figure 10-14 Half-bridge dc–dc converter.

Chap.10 Switching dc Power Supply

— dc-dc Converters with Electrical Isolation —

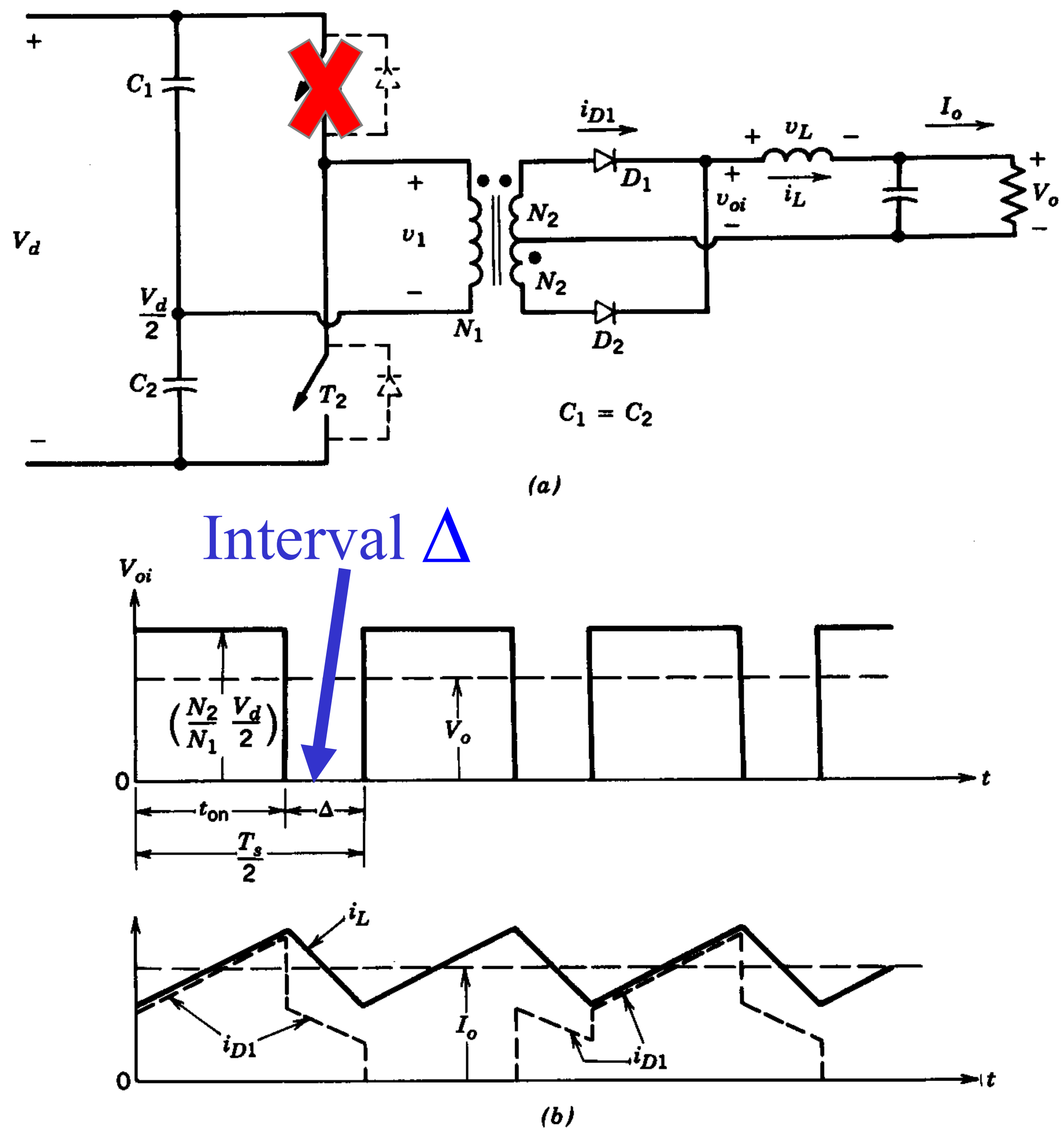


Figure 10-14 Half-bridge dc–dc converter.

T_1 is on

$$v_{oi} = (N_2/N_1)(V_d/2)$$

$$v_L = \frac{N_2}{N_1}\frac{V_d}{2} - V_o \quad 0 < t < t_{on}$$

Interval Δ

$$v_{oi} = 0$$

$$v_L = -V_o \quad t_{on} < t < t_{on} + \Delta$$

Chap.10 Switching dc Power Supply

— dc-dc Converters with Electrical Isolation —

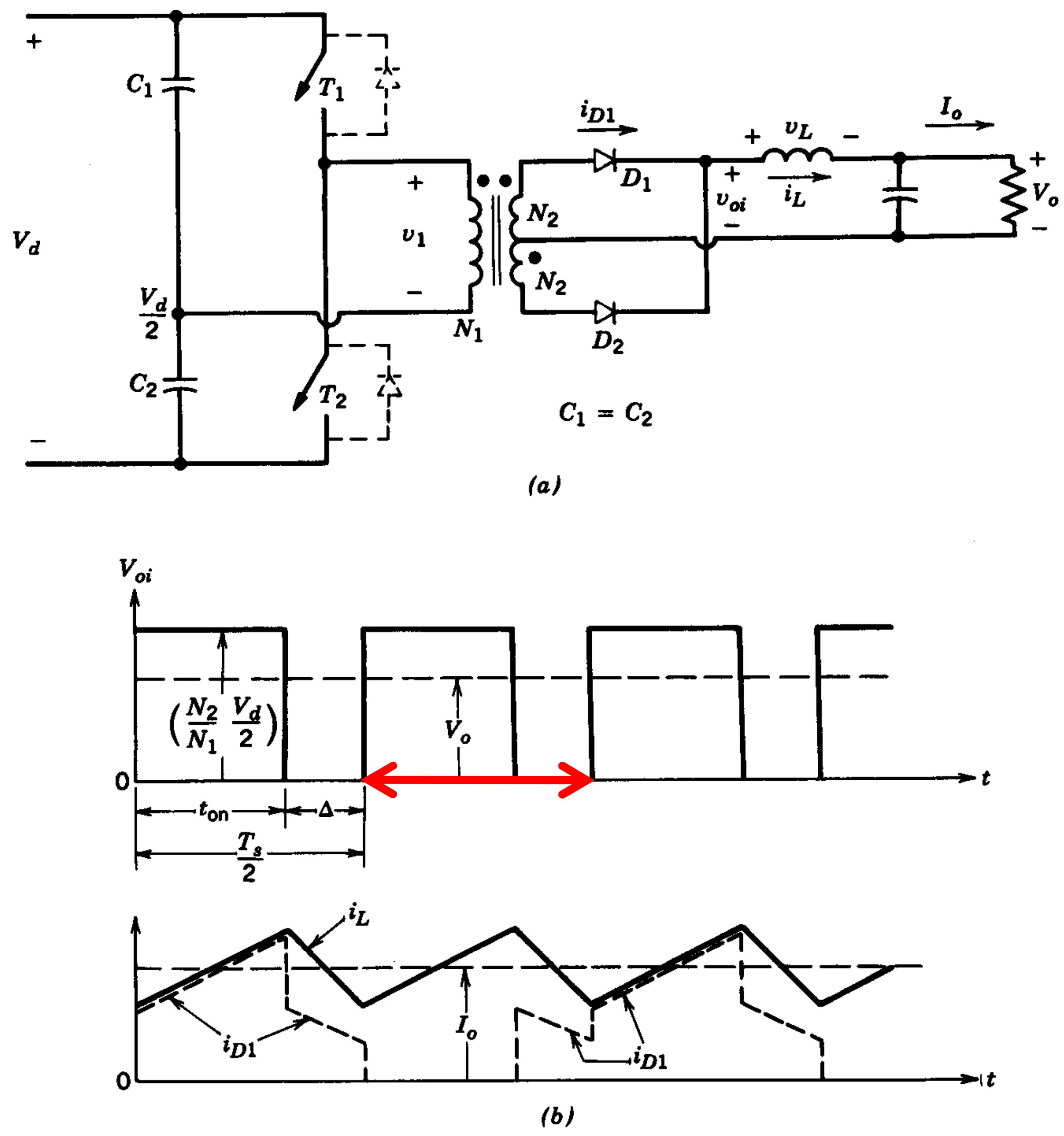


Figure 10-14 Half-bridge dc−dc converter.

10.4.5 Half-Bridge Converter（半桥变换器）

- The waveforms of the next half-cycle repeat with a period $T_s/2$, which consists of t_{on} (T_2 is on) and the interval Δ;

$$t_{on} + \Delta = \frac{1}{2}T_s$$

Chap.10 Switching dc Power Supply

— dc-dc Converters with Electrical Isolation —

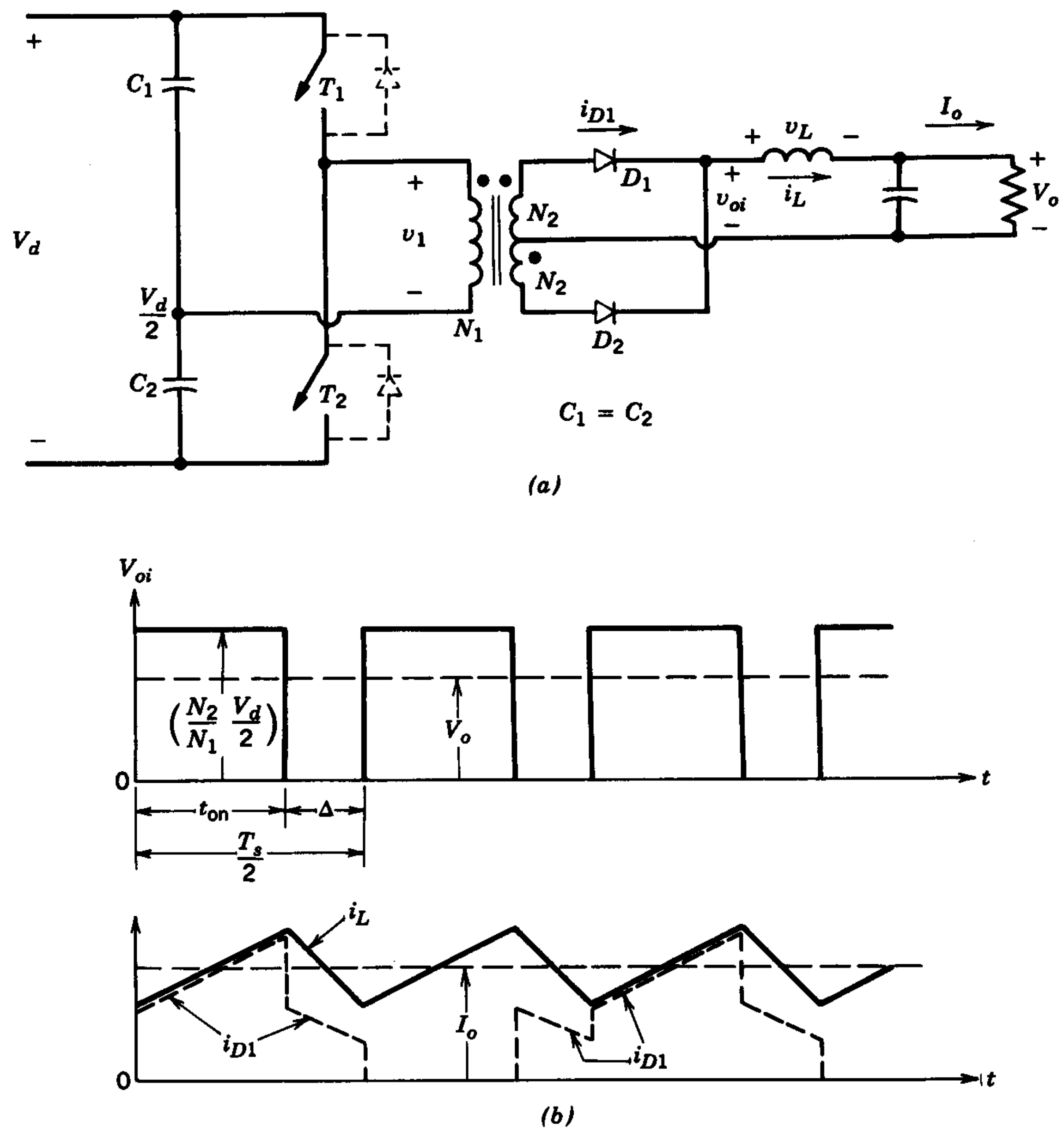


Figure 10-14 Half-bridge dc–dc converter.

- Equating the time interval of the inductor voltage during $T_s/2$ to zero yields,

$$v_L = \frac{N_2}{N_1}\frac{V_d}{2} - V_o \quad 0 < t < t_{on}$$

$$v_L = -V_o \quad t_{on} < t < t_{on} + \Delta$$

$$t_{on} + \Delta = \frac{1}{2}T_s$$

$$\frac{V_o}{V_d} = \frac{N_2}{N_1}D \quad 0 < D < 0.5$$

$$D = t_{on}/T_s$$

— dc-dc Converters with Electrical Isolation —

erter（全桥变换器）

- When T_1, T_2 or T_3, T_4 are on,

$$v_{\mathrm{oi}} = \frac{N_2}{N_1} V_{\mathrm{d}}$$

$$v_{\mathrm{L}} = \frac{N_2}{N_1} V_{\mathrm{d}} - V_{\mathrm{o}} \quad 0 < t < t_{\mathrm{on}}$$

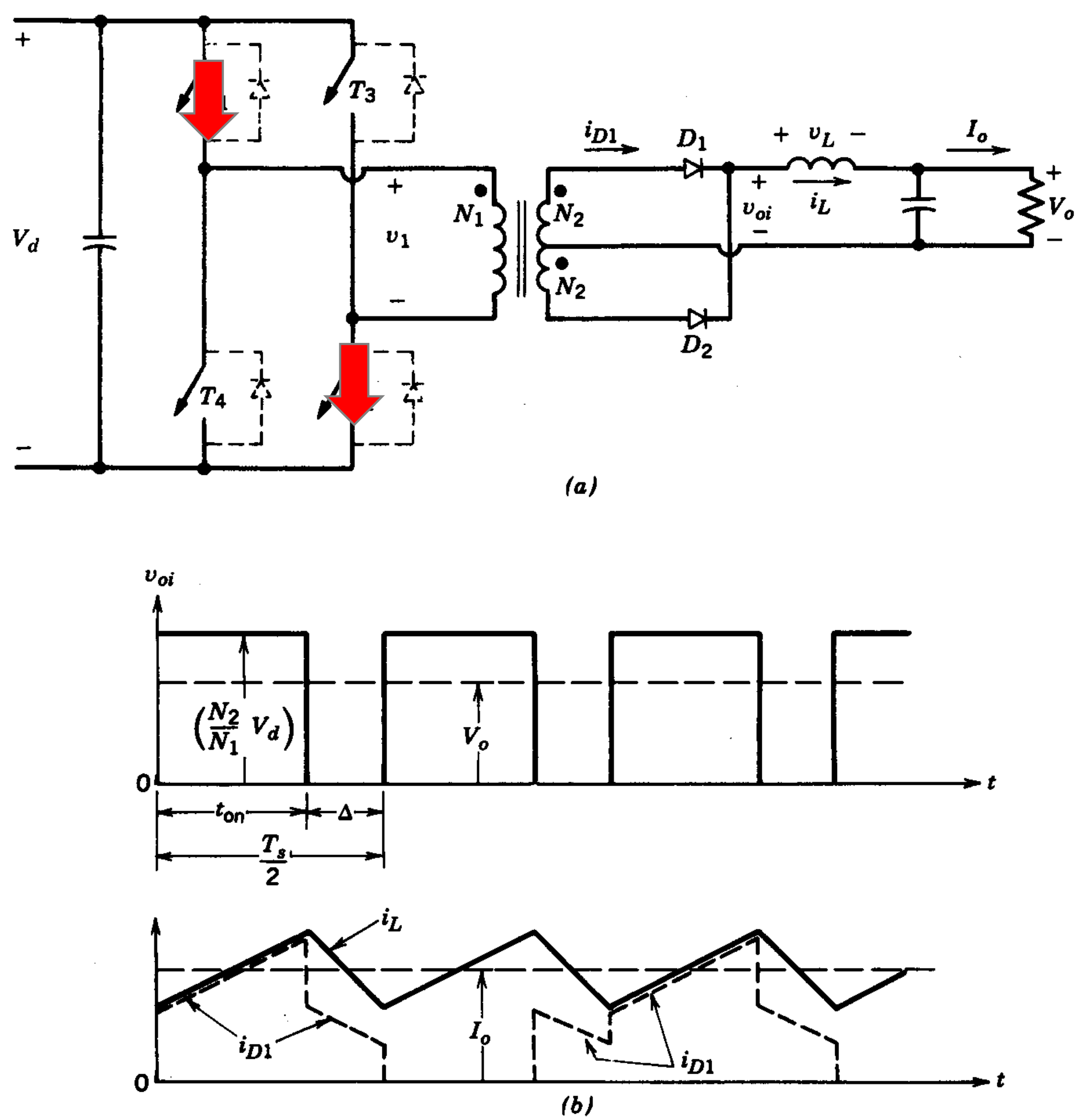


Figure 10-15 Full-bridge converter.

Chap.10 Switching dc Power Supply

— dc-dc Converters with Electrical Isolation —

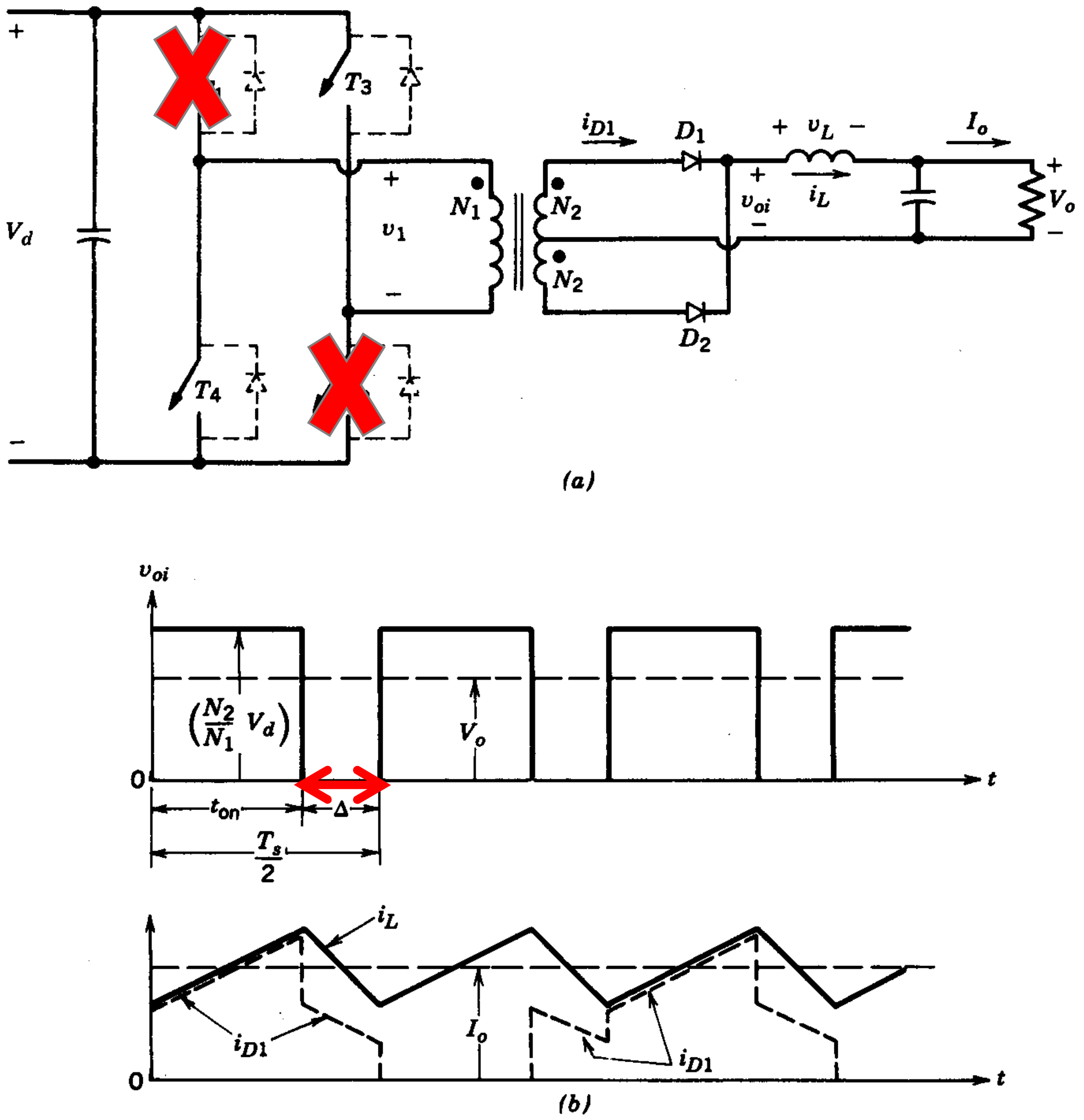


Figure 10-15 Full-bridge converter.

- When T_1, T_2 or T_3, T_4 are on,

$$v_{oi} = \frac{N_2}{N_1} V_d$$

$$v_L = \frac{N_2}{N_1} V_d - V_o \quad 0 < t < t_{on}$$

- When both the switches are off,

$$v_{oi} = 0$$

$$v_L = -V_o \quad t_{on} < t < t_{on} + \Delta$$

— dc-dc Converters with Electrical Isolation —

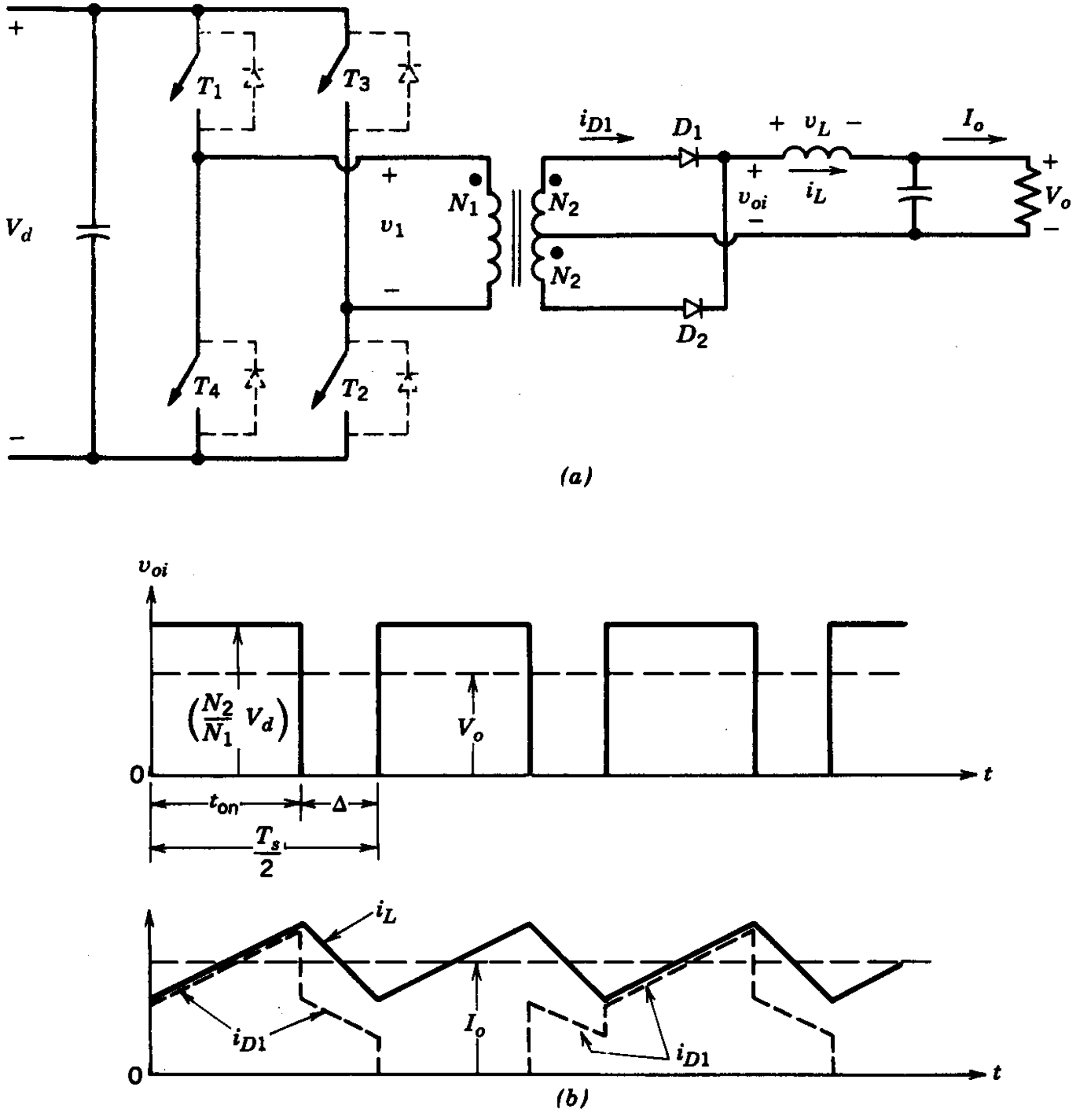


Figure 10-15 Full-bridge converter.

- Equating the time integral of the inductor voltage over one time period to zero in steady state and recognizing that $t_{\text{on}} + \Delta = \frac{T_s}{2}$ yield,

$$v_L = \frac{N_2}{N_1} V_d - V_o \quad 0 < t < t_{\text{on}}$$

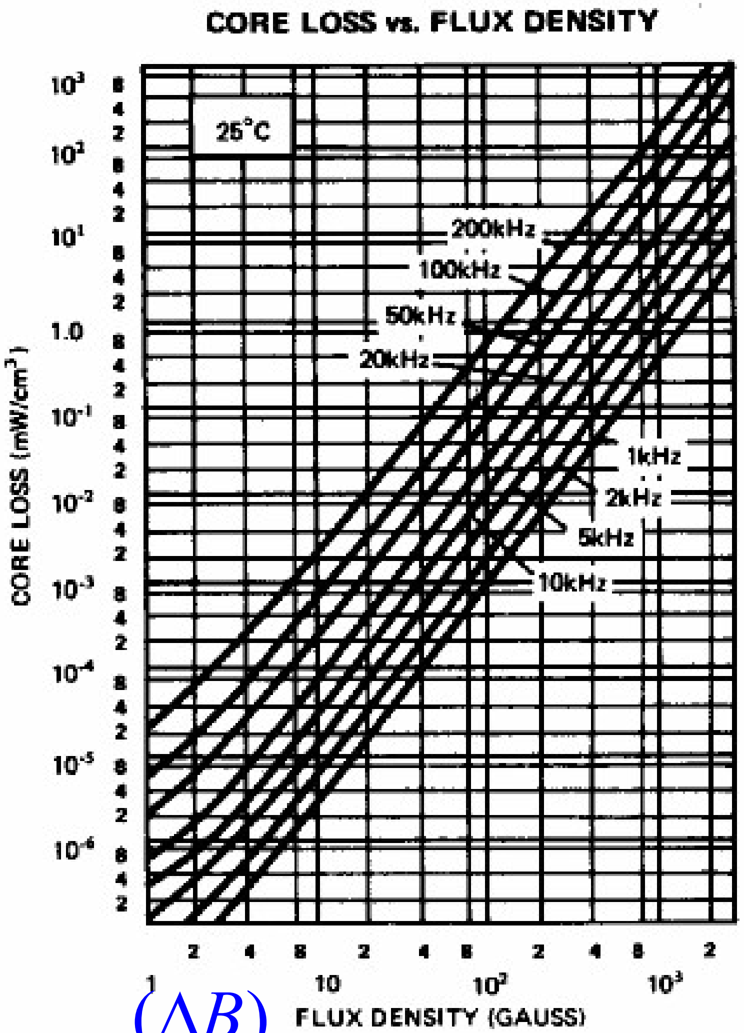
$$v_L = -V_o \quad t_{\text{on}} < t < t_{\text{on}} + \Delta$$

$$\frac{V_o}{V_d} = 2\frac{N_2}{N_1} D \ , 0 < D < 0.5$$

$$D = t_{\text{on}} / T_s$$

— dc-dc Converters with Electrical Isolation —

10.4.8 Transformer Core Selection in dc-dc converters with Electrical Isolation



$(\Delta B)_{max}$

Core loss curves

- The core loss per unit volume for several switching frequencies is plotted as a function of $(\Delta B)_{max}$,

$$\text{Core loss density} = k f_s^{\,a}[(\Delta B)_{max}]^b$$

- $(\Delta B)_{max}$ is the peak swing in the flux density around its average value during each switching cycle.

- *k*, *a* and *b* depend on the type of material.

- In both converters (forward converter and full-bridge converter),

$$(\Delta B)_{\max} = \frac{V_{\mathrm{d}}}{4N_1 A_c f_s} \quad (\text{at } D = 0.5)$$

- A_{c} is the cross-sectional area and N_1 is the number of turns in the primary winding.

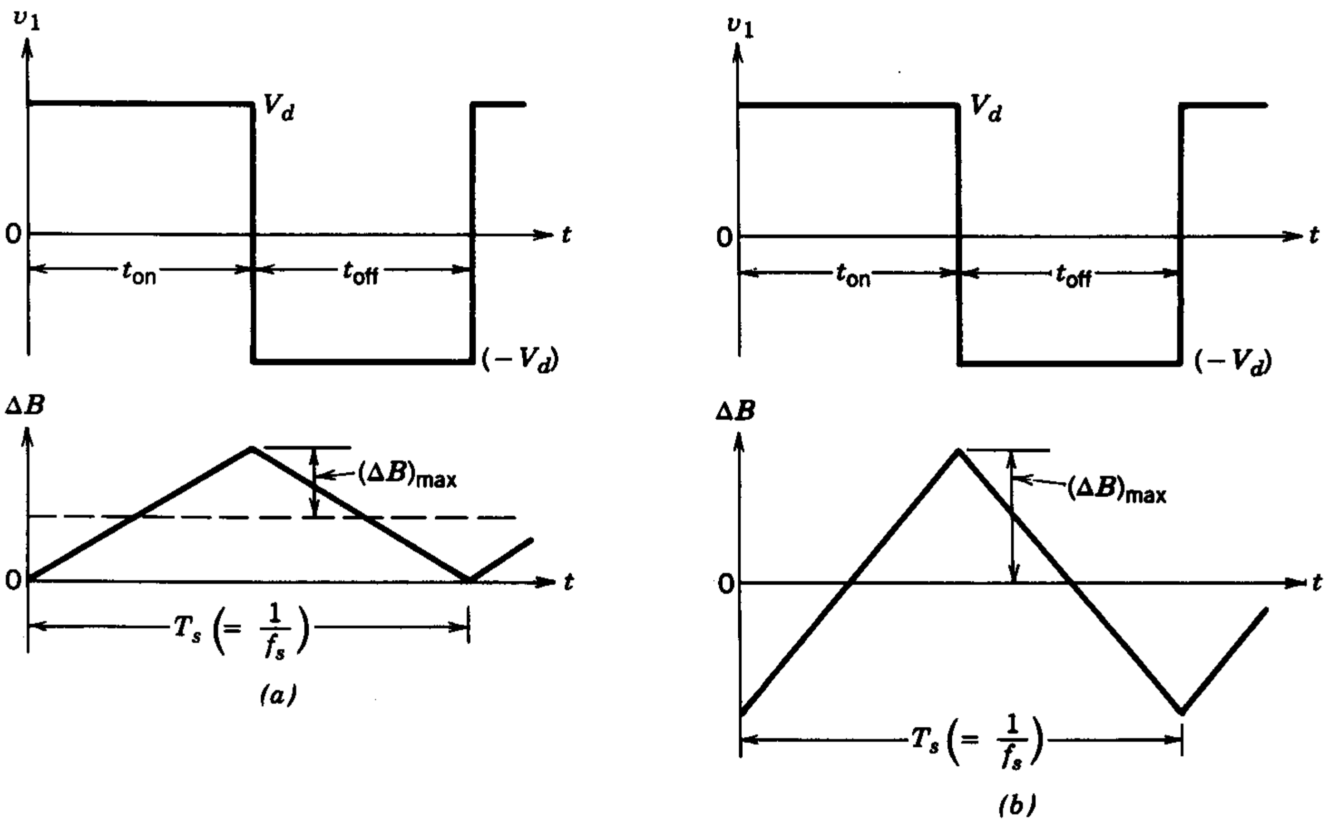
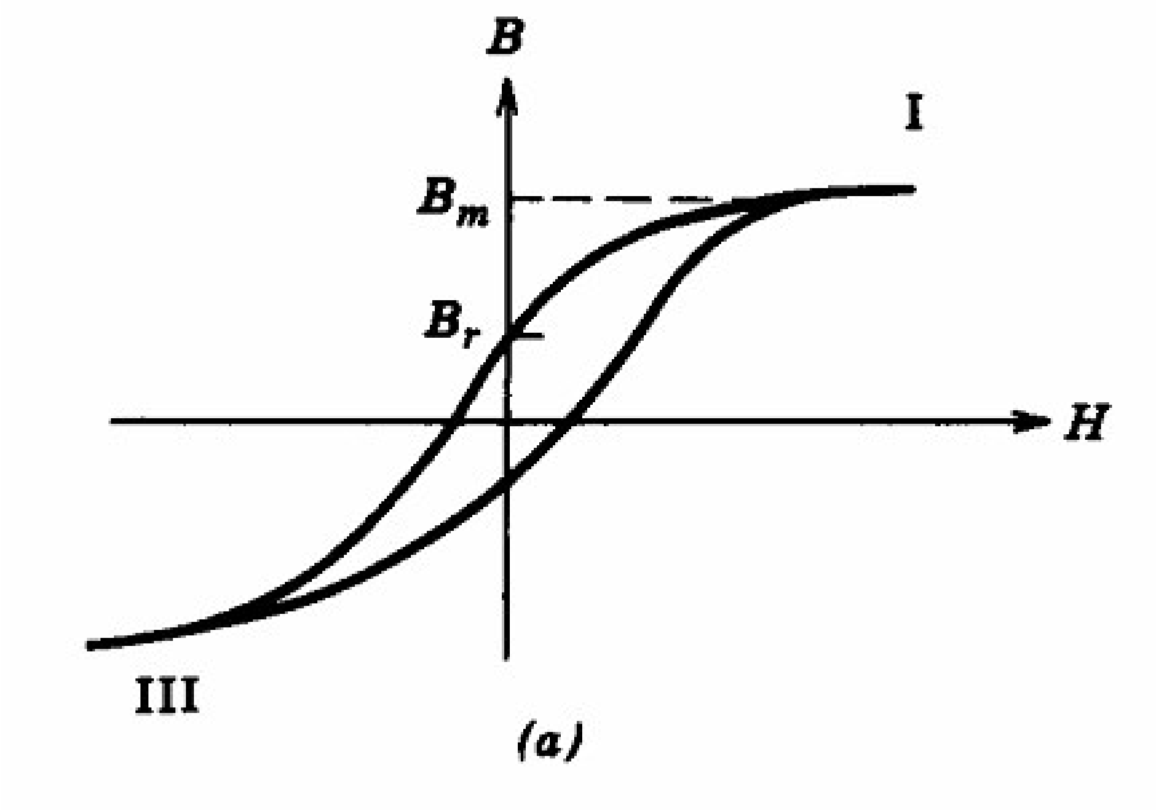


Figure 10-18 Core excitation: (*a*) forward converter, $D = 0.5$; (*b*) full-bridge converter, $D = 0.5$.

• In both converters (forward converter and full-bridge converter),

$$(\Delta B)_{\max} = \frac{V_{\mathrm{d}}}{4N_1 A_c f_s} \quad (\text{at } D = 0.5)$$

• A_{c} is the cross-sectional area and N_1 is the number of turns in the primary winding.



Typical *B-H* loop of transformer core

• In the forward converter with a unidirectional core excitation,

$$(\Delta B)_{\max} < \frac{1}{2}(B_{\mathrm{m}} - B_{\mathrm{r}})$$

• In the full-bridge converter with a bidirectional core excitation,

$$(\Delta B)_{\max} < B_{\mathrm{m}}$$

Chap.10 Switching dc Power Supply

– Control of Switch-Mode dc Power Supplies –

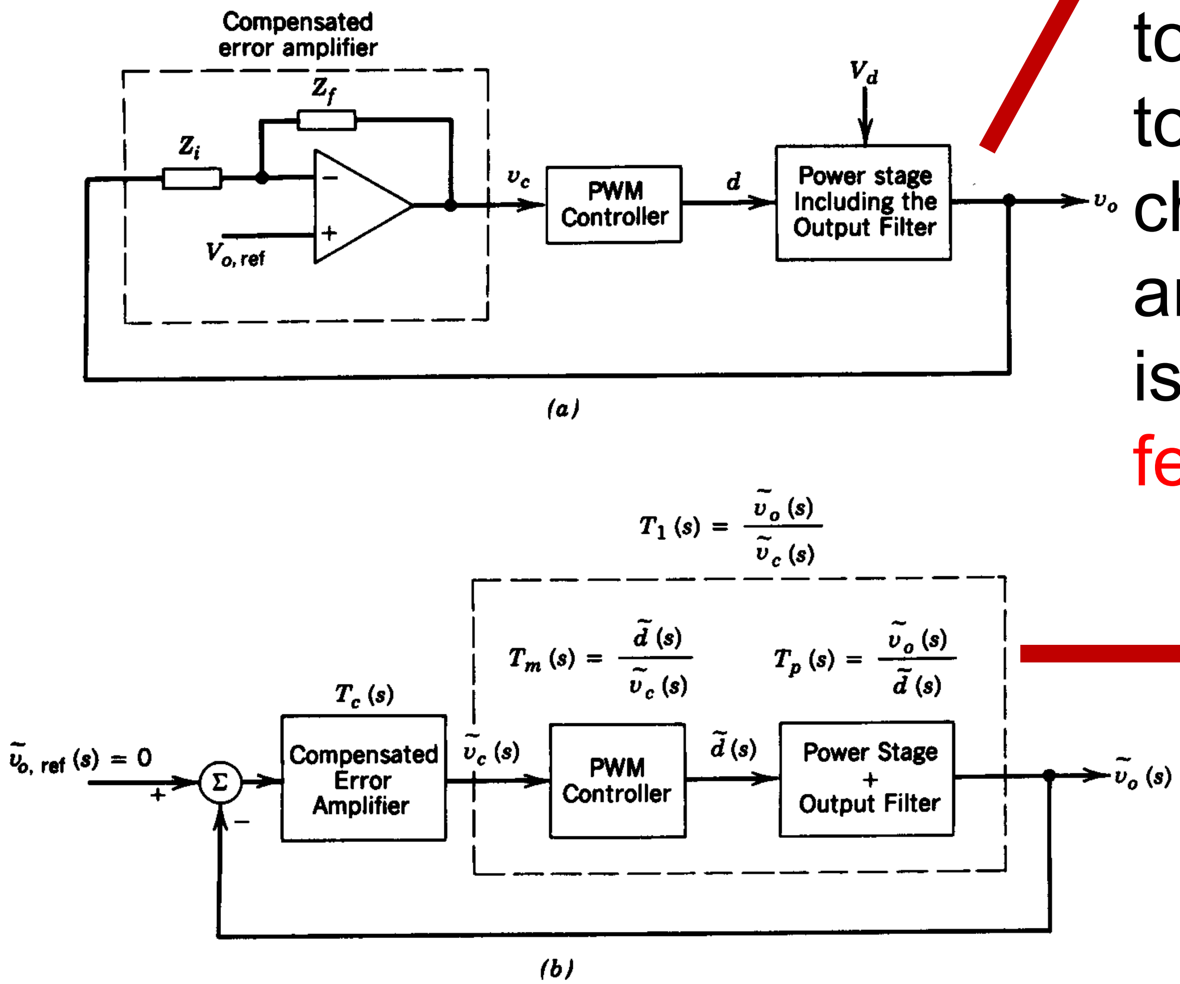


Figure 10-19 Voltage regulation: (*a*) feedback control system; (*b*) linearized feedback control system.

- The output voltages of dc power supplies are regulated to be within a specified tolerance band in response to changes in the output load and the input voltages, which is realize by a negative-feedback control system.

- The power stage and controllers can be linearized around a steady-state operating point, where the small ac signals are represented by " ~ ".

– Control of Switch-Mode dc Power Supplies –

• If the input voltage changes, an error is produced in the output voltage, which eventually gets corrected by the feedback control. This results in a slow dynamic performance in regulating the output in response to the changes in input voltage.

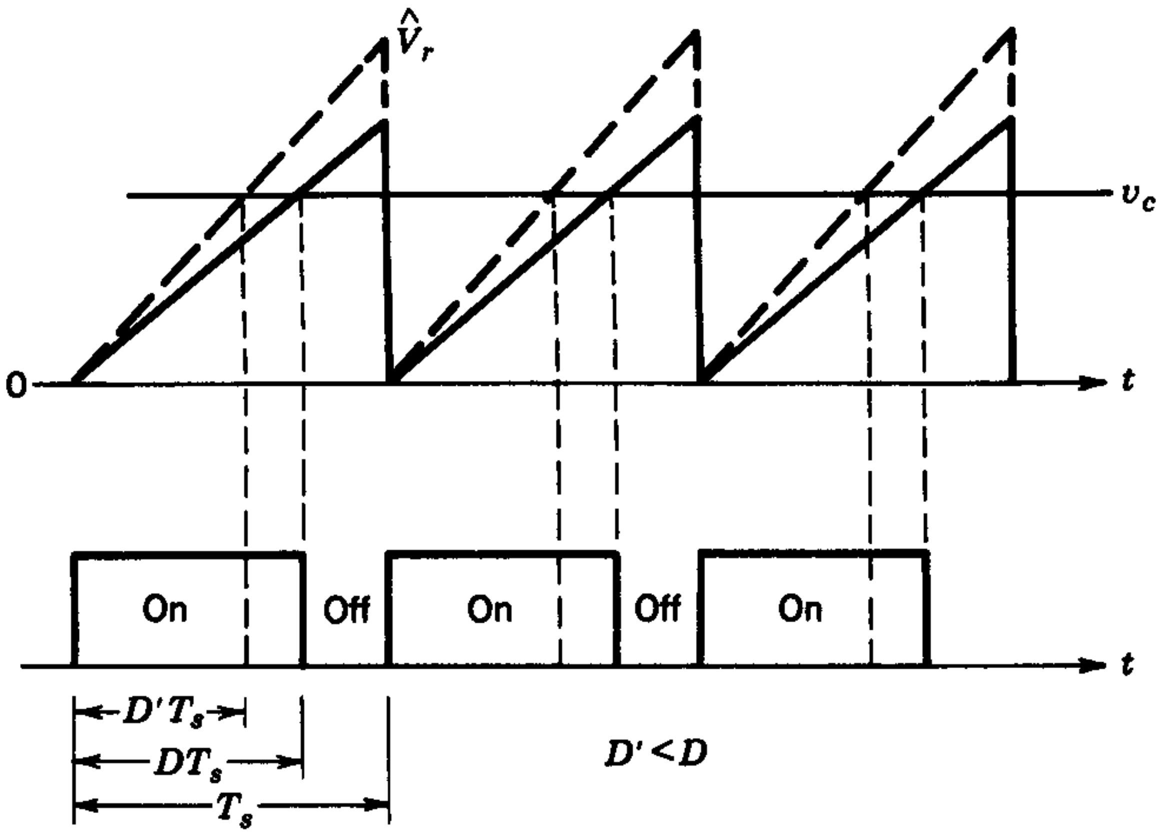


Figure 10-28 Voltage feed-forward: effect on duty ratio.

Voltage feed-forward

• The ramp (and the peak) of the sawtooth waveform does not stay constant but varies in direct proportion to the input voltage. Thus, an increased input voltage results in a decreased duty ratio.

Chap.10 Switching dc Power Supply

– Control of Switch-Mode dc Power Supplies –

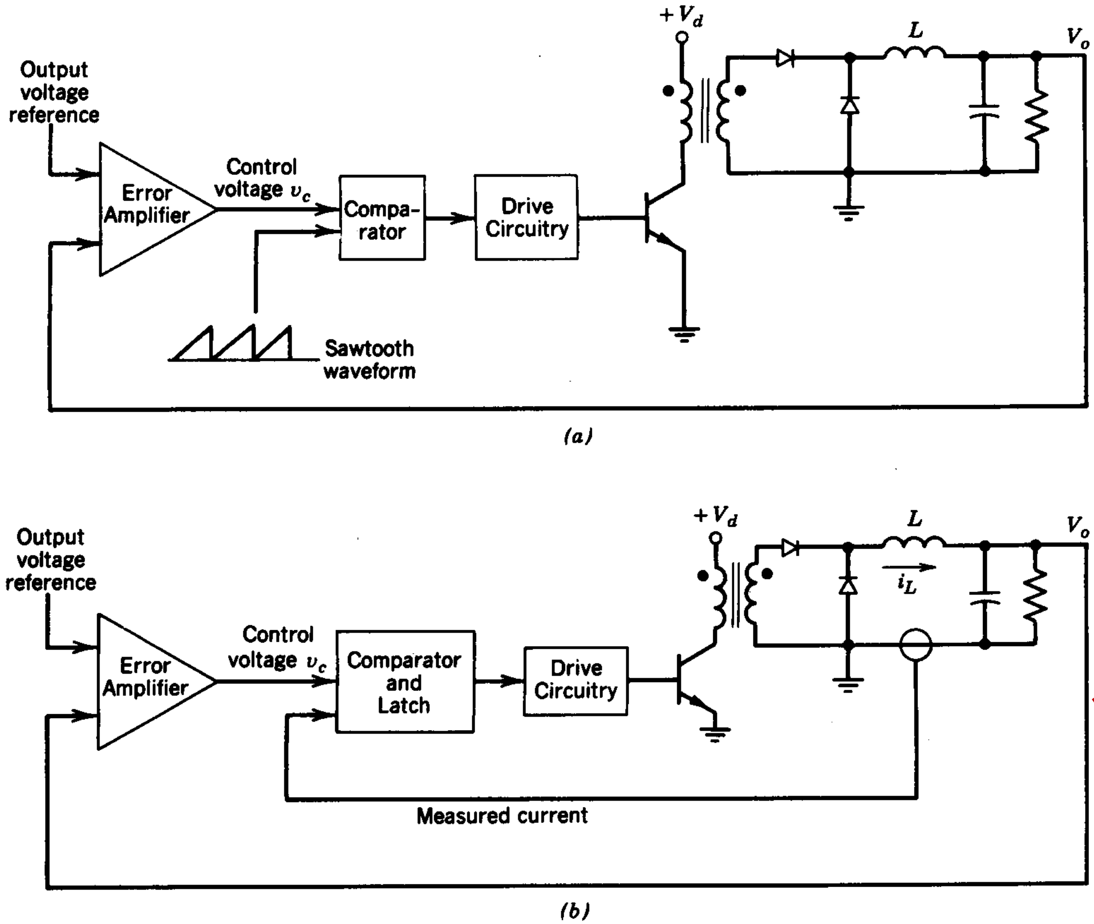


Figure 10-29 PWM duty ratio versus current-mode control: (*a*) PWM duty ratio control; (*b*) current-mode control.

PWM direct duty ratio control

- The control voltage v_c controls the duty ratio by comparing the control voltage with a fixed-frequency sawtooth waveform.

Current-mode control

- An additional inner control loop is used, where the control voltage v_c directly controls the output inductor current that feeds the output stage.

– Control of Switch-Mode dc Power Supplies –

The current-mode control has several advantages over the conventional direct duty ratio PWM control

- It limits peak switch current.
- It removes one pole (corresponding to the output filter inductor) from the control-to-output transfer function $\tilde{v}_o(s)/\tilde{v}_c(s)$, thus simplifying the compensation in the negative-feedback system.
- It allows a modular design of power supplies by equal current sharing.
- It results in a symmetrical flux excursion in a push-pull converter, thus eliminating the problem of transformer core saturation.

Summary & Discussion

Requirements for dc Power Supplies

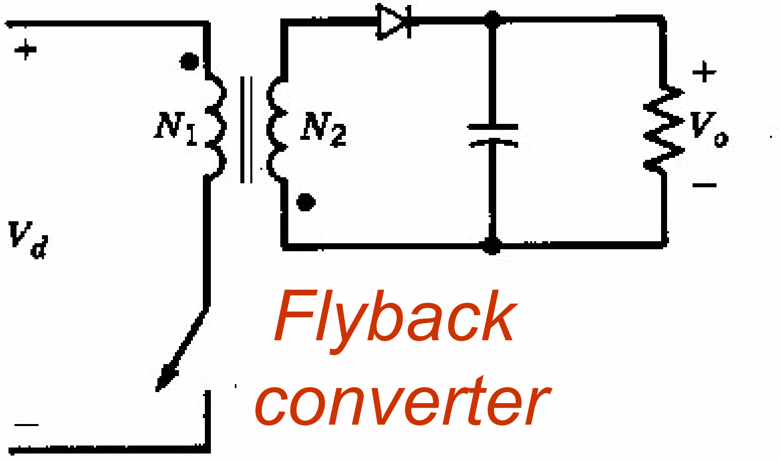
Regulated output;

Isolation;

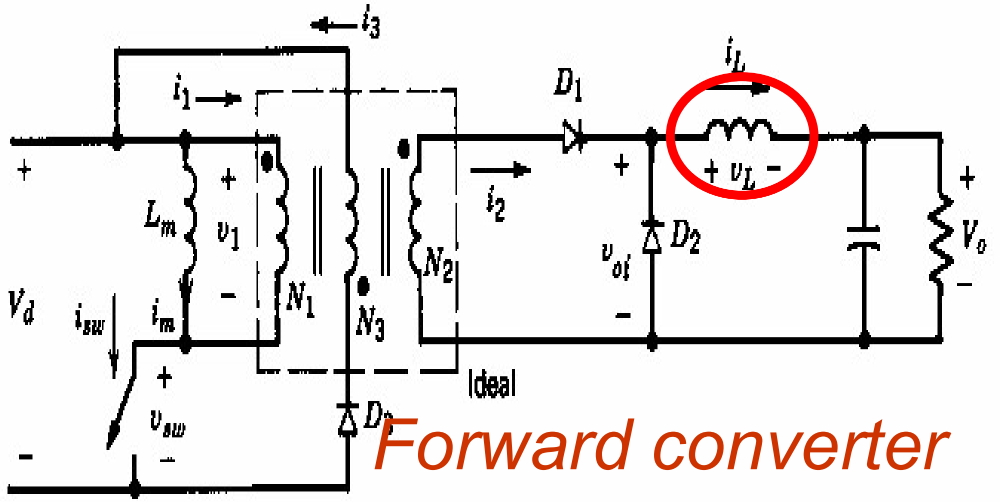
Multiple output.

Major advantages of switching power supplies

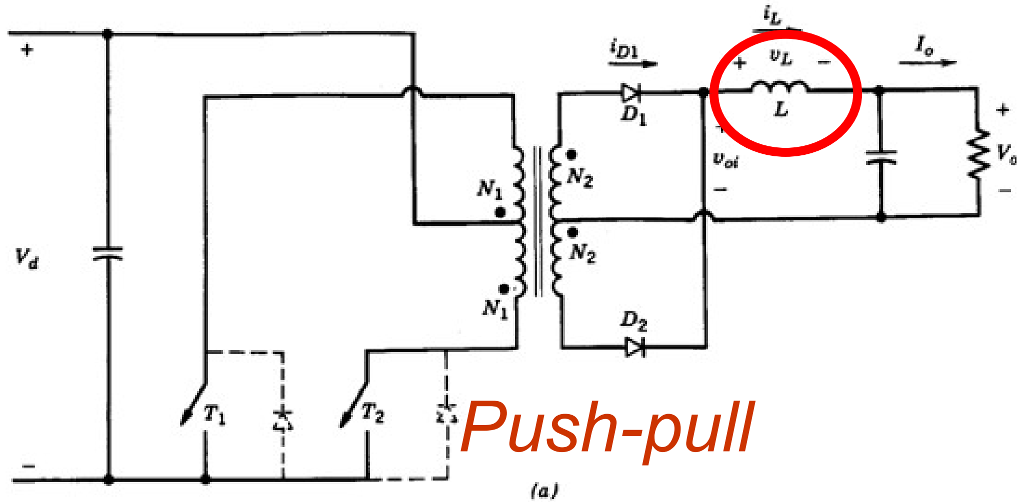
- *higher energy efficiency*
- *reduced size and weight*



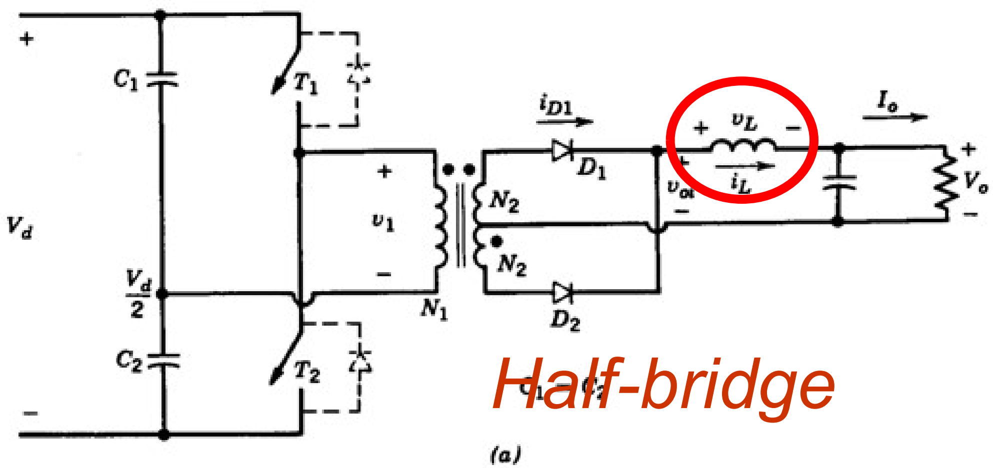
Flyback converter



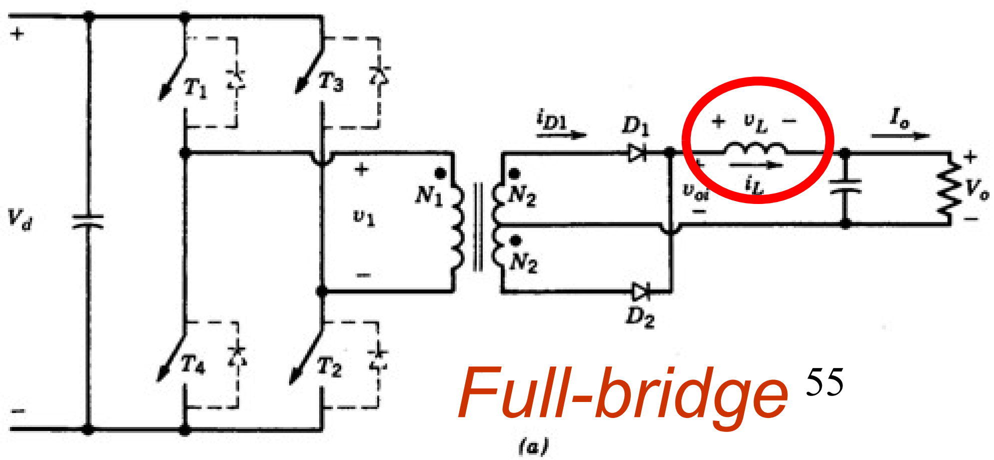
Forward converter



Push-pull



Half-bridge



Full-bridge

Summary & Discussion

How to obtain the voltage transfer ratio?

For the converters without output filter inductor

The change of flux through the core over one time period must be zero in steady state.

$$\phi(T_s) = \phi(0)$$

For the converters with output filter inductor

Equating the integral of the inductor voltage over one time period to zero.

Chap.10 Switching dc Power Supply

Vocabulary

1. switching power supply	n.	开关电源
2. linear power supply	n.	线性电源
3. active region	n.	放大区
4. flyback converter	n.	反激变换器
5. forward converter	n.	正激变换器
6. push-pull	n.	推挽
7. half bridge	n.	半桥
8. full bridge	n.	全桥
9. transformer core	n.	变压器铁心
10. center-tapped secondary	n.	中间抽头副边
11. flux density	n.	磁密,磁感应强度
12. cross-sectional area	n.	截面面积
13. EMI	n.	电磁干扰
14. voltage transfer ratio	n.	电压传输比
15. thermister	n.	热敏电阻

Reference

《开关电源的原理与设计》

张占松，蔡宣三 编著

电子工业出版社