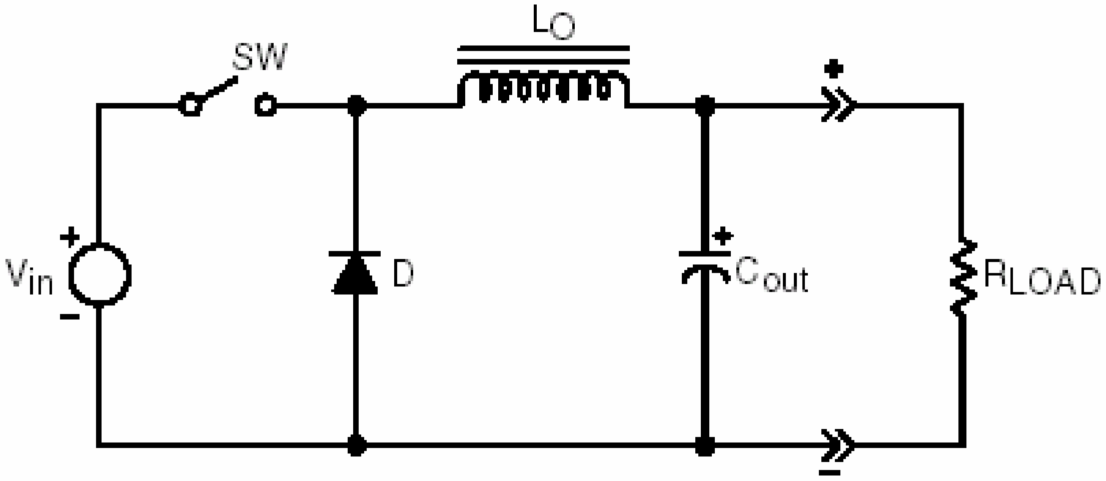
Technical Training

Adlsong

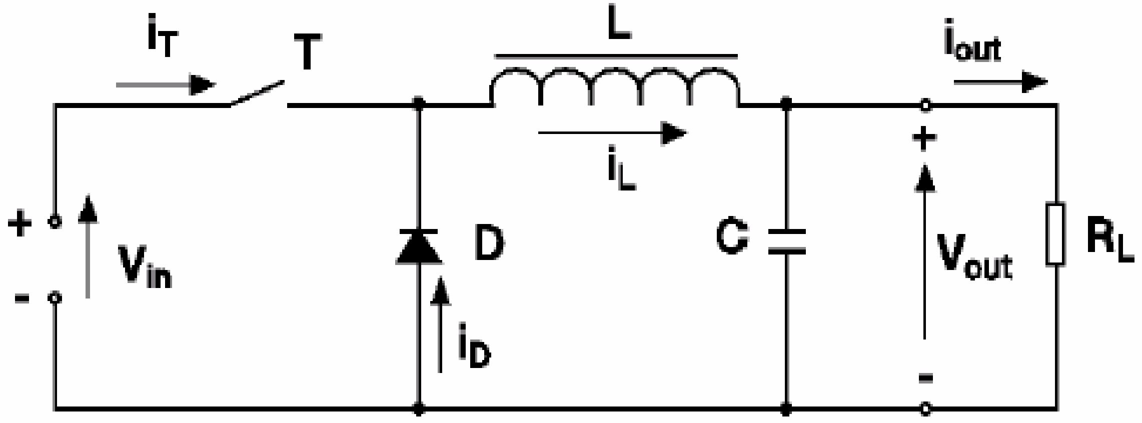
SMPS Topologies

The Buck Converter

Buck



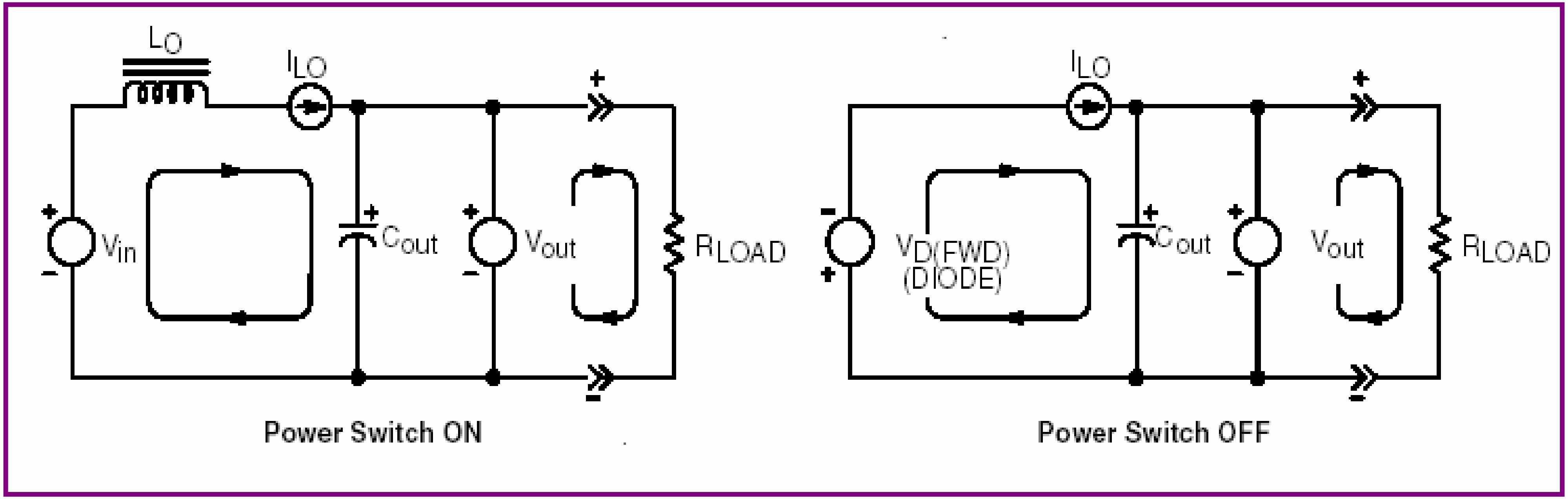
A Basic Forward-Mode Converter



Buck Converter

Step Down Voltage Regulator

Buck



State 1: S is on, the inductor current rises linearly:

$$L\frac{di_L}{dt} = V_{in} - V_o \qquad \Delta I_{pk} = \frac{(V_{in} - V_o)D}{Lf_S}$$

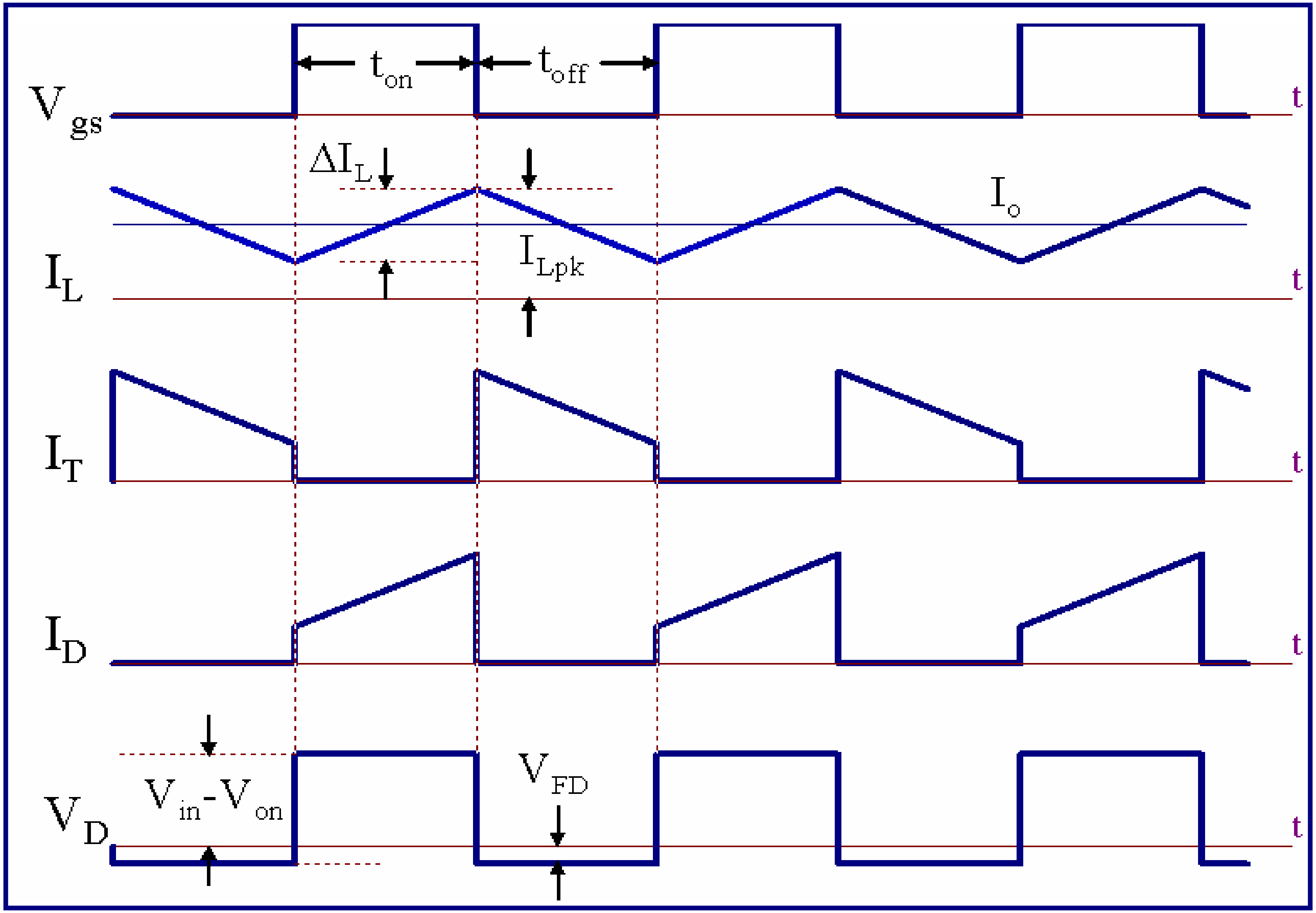
State 2: S is off, the inductor current decreases linearly:

$$-L\frac{di_L}{dt} = V_o \qquad \Delta I_{pk} = \frac{V_o(1-D)}{Lf_S}$$

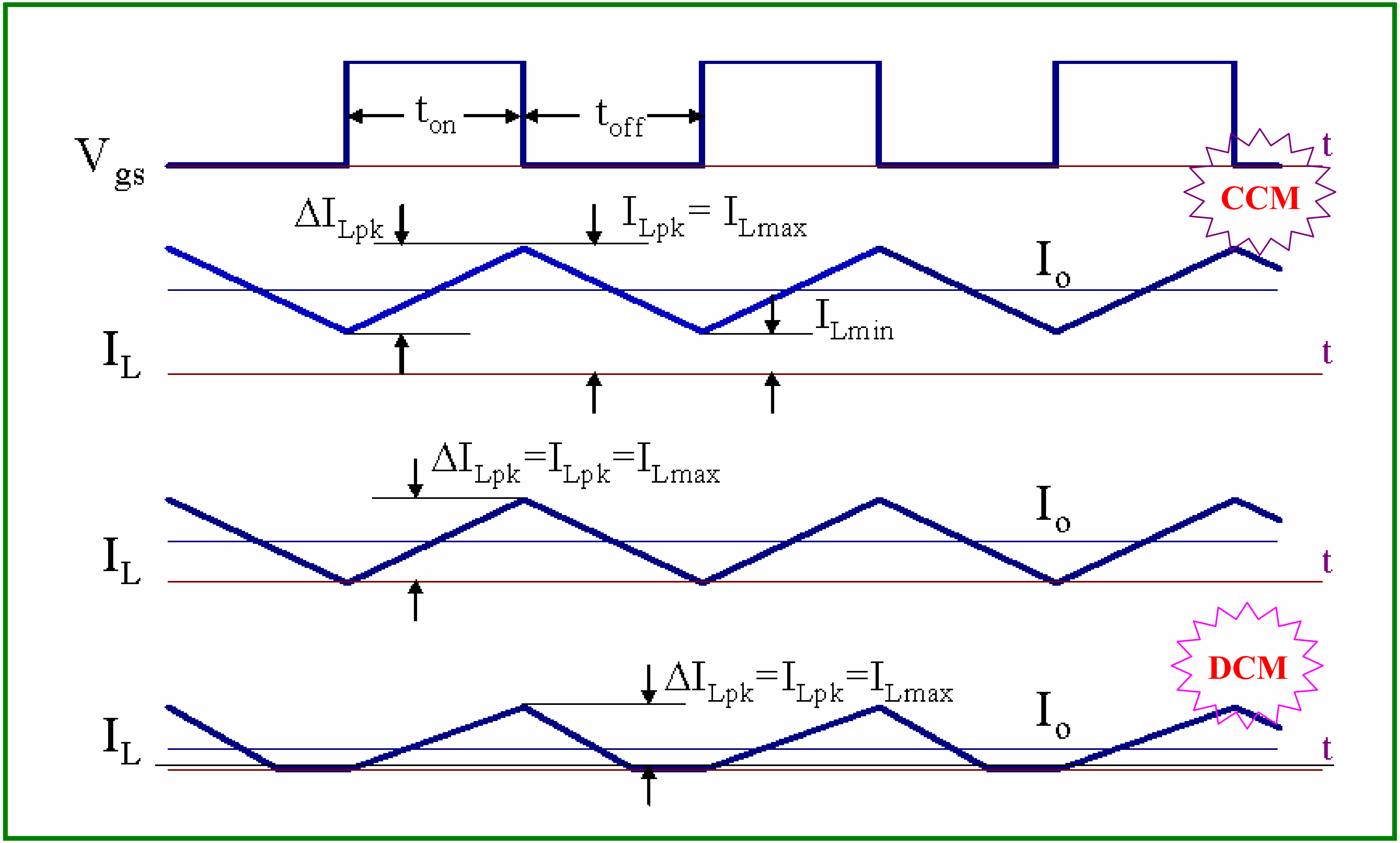
Volts Second Balance: $V_o = DV_{in}$, $D = T_{on}/T$

$V_{in} \cdot I_{in} = V_o \cdot I_o$, $I_{in} = I_L = I_o/D$

Buck



Buck



t_{on}
t_{off}
V_{gs}
t
CCM
ΔI_{Lpk}
$I_{Lpk} = I_{Lmax}$
I_o
I_{Lmin}
I_L
t
$\Delta I_{Lpk} = I_{Lpk} = I_{Lmax}$
I_o
I_L
t
DCM
$\Delta I_{Lpk} = I_{Lpk} = I_{Lmax}$
I_o
I_L
t

Buck

The voltage ripple of output capacitor:

$i_L > I_o$, C_{out} is charged

1) Integral during the period

$$\Delta U_o = \frac{1}{C}\int_{\frac{Ton}{2}}^{Ton} i_C dt + \frac{1}{C}\int_{Ton}^{Ton+\frac{Toff}{2}} i_C dt$$

$$= \frac{(1-D)V_o}{8L_f C_{out} f_S{}^2}$$

2) The charge during the period

$$\Delta Q = \frac{1}{2}\frac{\Delta I_{Lpk}}{2}\frac{T_s}{2}$$

$$\Delta U_o = \frac{\Delta Q}{C_{out}} = \frac{(1-D)V_o}{8L_f C_{out} f_S{}^2}$$

Take ESR into Account: $\Delta U_o = ESR \bullet \Delta I_{Lpk} = \dfrac{(1-D)V_o \bullet ESR}{L_f f_S}$

Buck

Critical condition between DCM and CCM

$$I_o = \frac{1}{2} I_{L\max} = \frac{(V_{in} - V_o)D}{2L_f f_S}$$

Power Balance

DCM

$$I_o < \frac{1}{2} I_{L\max} = \frac{(V_{in} - V_o)D}{2L_f f_S}$$

Volts-Sec Balance

$$T_{off} = D'T_S = \frac{(V_{in} - V_o)D}{V_o} T_S < (1 - D)T_S$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{D}{D + D'}}$$

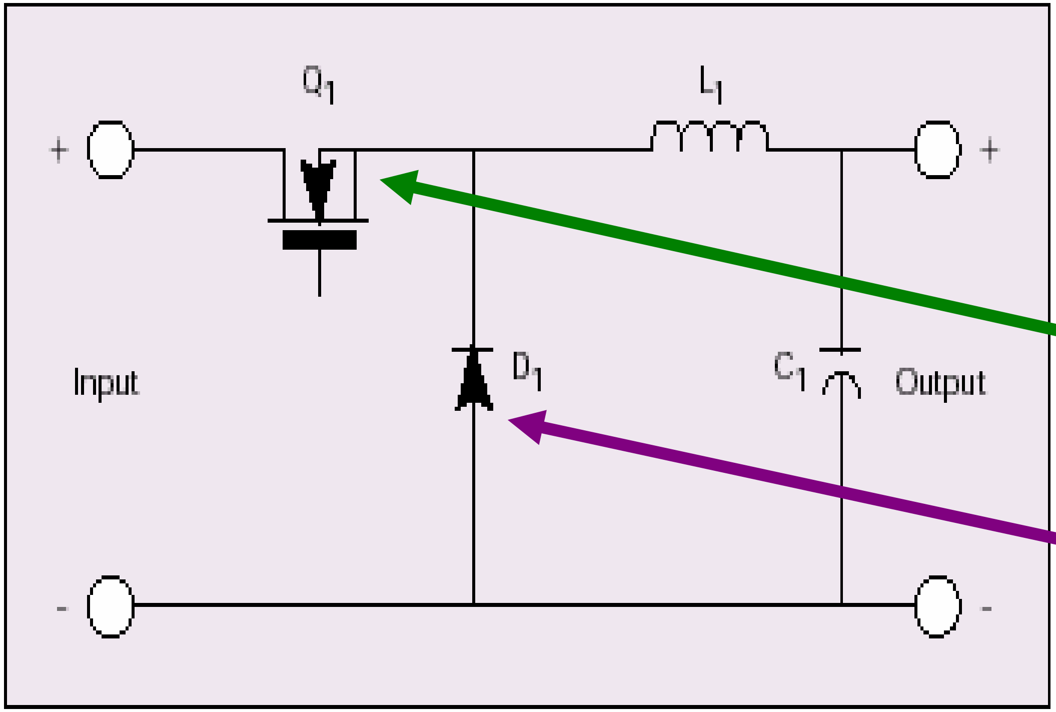
$$\boxed{I_o = \frac{1}{2} I_{L\max} \frac{T_{on} + T_{off}}{T_S} = \frac{D^2}{2Lf_S} V_{in} \frac{V_{in} - V_o}{V_o}}$$

Buck

Disadvantages: a limited power range

Advantages: simplicity and low cost

Useful Power Level: 1~50 W
Switch Voltage Stress: V_{in}
Switch Power Stress: P_{in}
Transformer Utilization: N/A
Duty Cycle: <1.0
Output Ripple Frequency: f_S
Relative Cost: Low



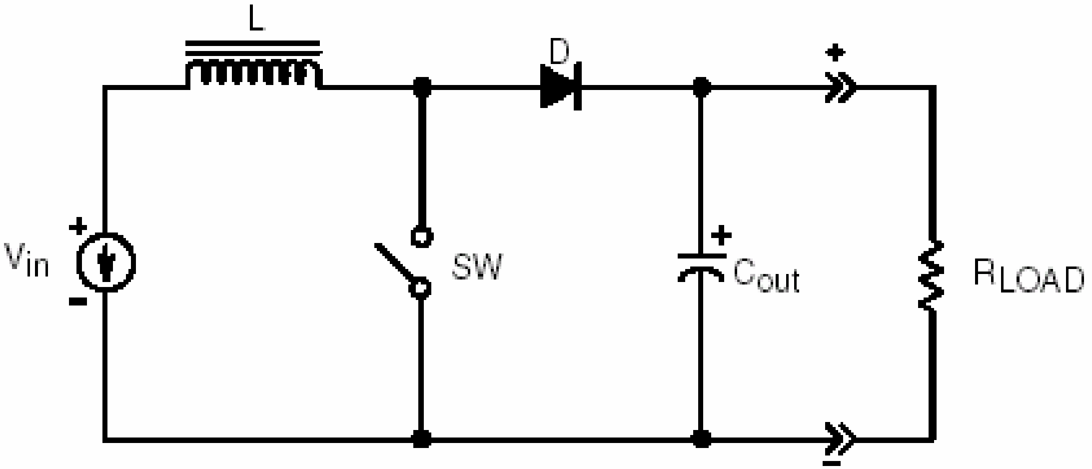
Power Switch:
$V_{DDS} > V_{inmax}$ $I_{Dmax} > I_o + \Delta I/2$

Rectifier:
$V_{RRM} > V_{inmax}$ $I_{F(AV)} > I_o(1-D)$

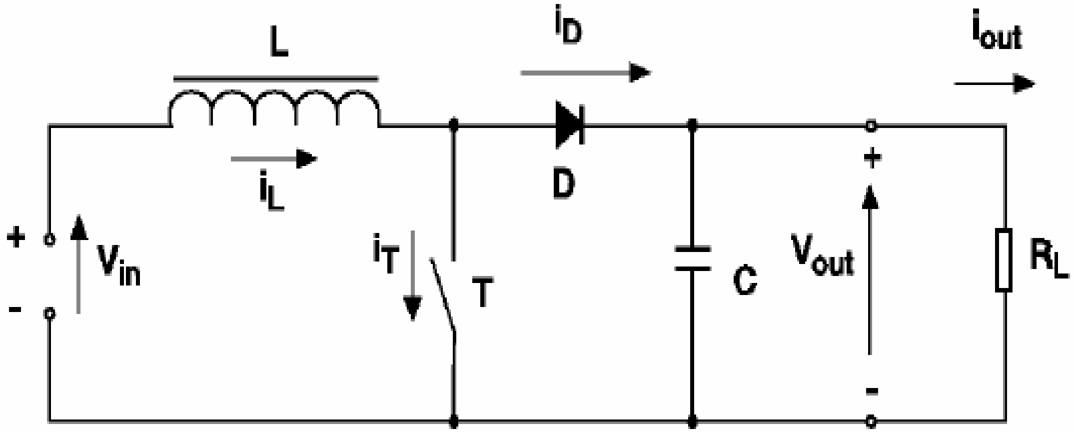
$f_S = 1/T_S$ $D = T_{on}/T_S$ $V_o = DV_{in}$

2 The Boost Converter

Boost



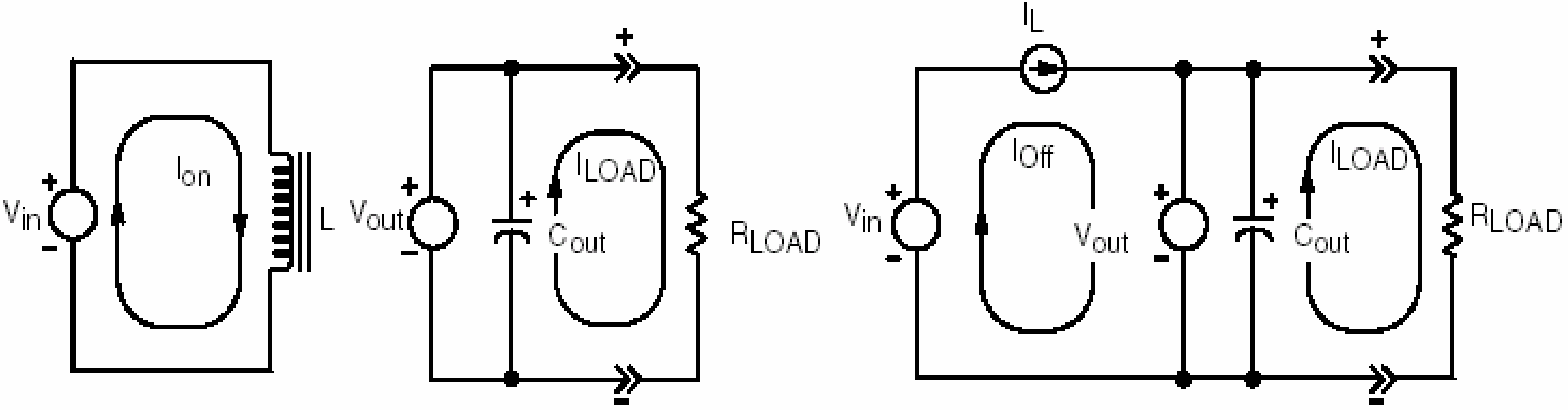
A Basic Flyback-Mode Converter



Boost Converter

Step Up Voltage Regulator

Boost



Power Switch ON

Power Switch OFF

State 1: S is on, the inductor current rises linearly:

$$L\frac{di_L}{dt} = V_{in} \qquad \Delta I_{pk} = \frac{V_{in}D}{Lf_S}$$

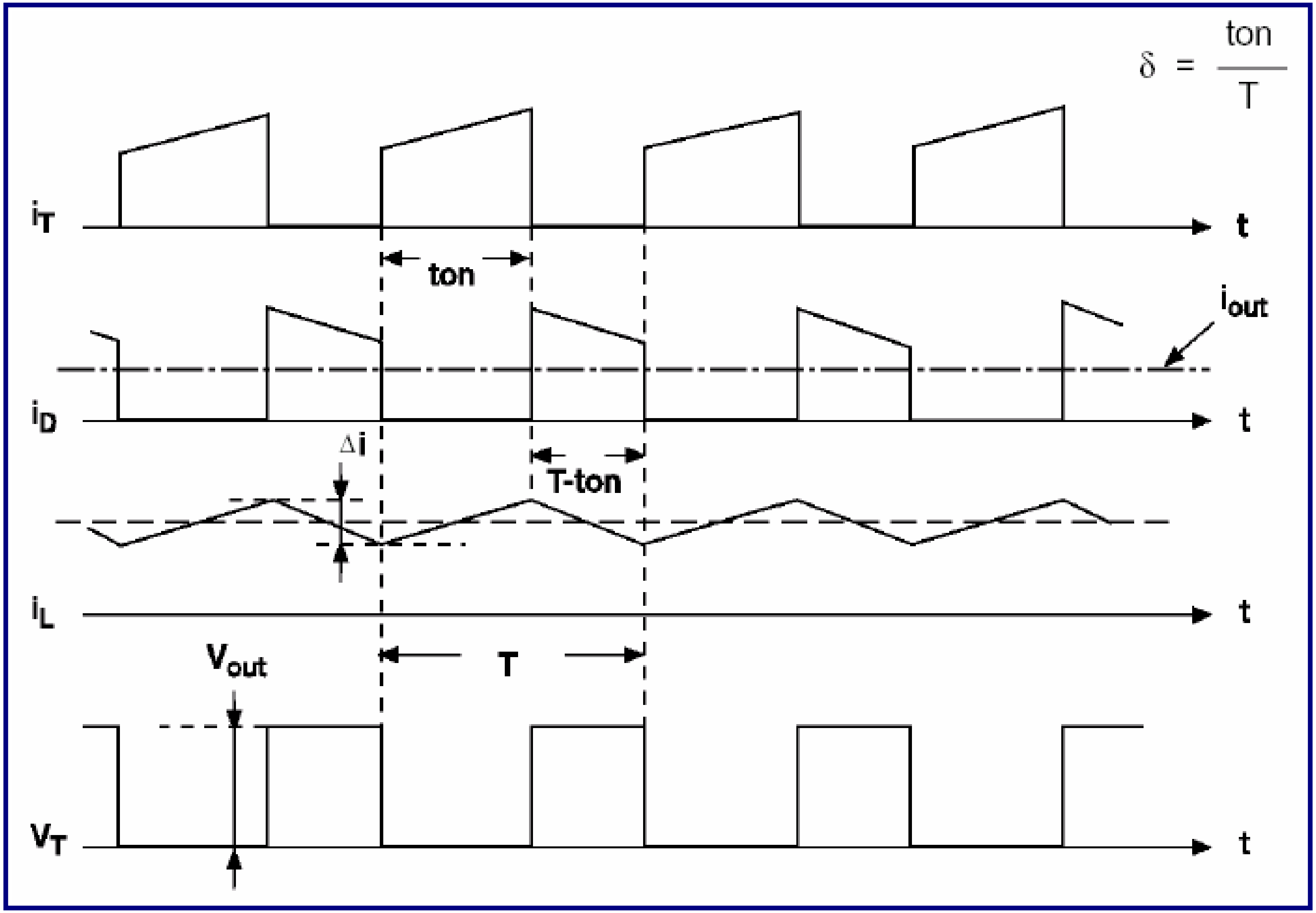
State 2: S is off, the inductor current decreases linearly:

$$-L\frac{di_L}{dt} = V_{in} - V_o \qquad \Delta I_{pk} = \frac{(V_o - V_{in})(1-D)}{Lf_S}$$

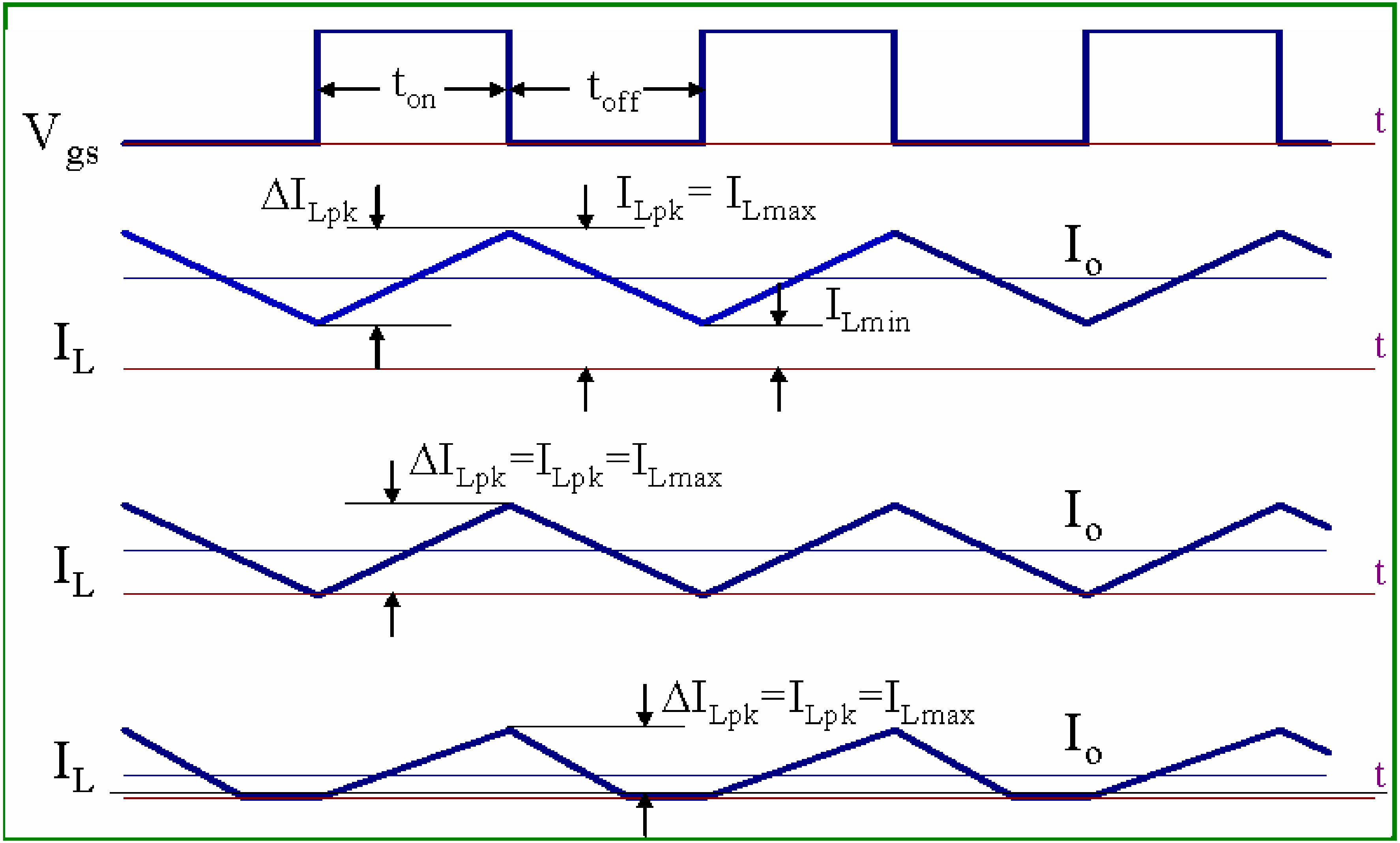
Volts Second Balance: $V_o = V_{in}/(1\text{-}D)$, $D = T_{on}/ T$

$V_{in} \cdot I_{in} = V_o \cdot I_o$, $\quad I_{in} = I_o\,(1\text{-}D)$

Boost



Boost



V_{gs}
t_{on}
t_{off}
t
ΔI_{Lpk}
$I_{Lpk} = I_{Lmax}$
I_o
I_{Lmin}
I_L
t
$\Delta I_{Lpk}=I_{Lpk}=I_{Lmax}$
I_o
I_L
t
$\Delta I_{Lpk}=I_{Lpk}=I_{Lmax}$
I_o
I_L
t

Boost

The voltage ripple of output capacitor:

$i_D > I_o$, C_{out} is charged

1) Integral during the period

$$\Delta U_o = \frac{1}{C}\int_0^{Ton} i_o dt$$

$$= \frac{DI_o}{C_{out} f_S}$$

2) The charge during the period

$$\Delta Q = DI_o T_s$$

$$\Delta U_o = \frac{\Delta Q}{C_{out}} = \frac{DI_o}{C_{out} f_S}$$

Take ESR into Account: $\Delta U_o = ESR \bullet \Delta I_{Lpk} = \frac{DV_{in} \bullet ESR}{L_f f_S}$

Boost

Critical condition between DCM and CCM

$$I_{in} = \frac{1}{2} I_{L\max} = \frac{V_{in} D}{2 L_f f_S}$$

Power Balance

Volts-Sec Balance

DCM

$$I_{in} < \frac{1}{2} I_{L\max} = \frac{V_{in} D}{2 L_f f_S}$$

$$T_{off} = D' T_S = \frac{V_{in} D}{V_o - V_{in}} T_S < (1 - D) T_S$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{D + D'}{D'}}$$

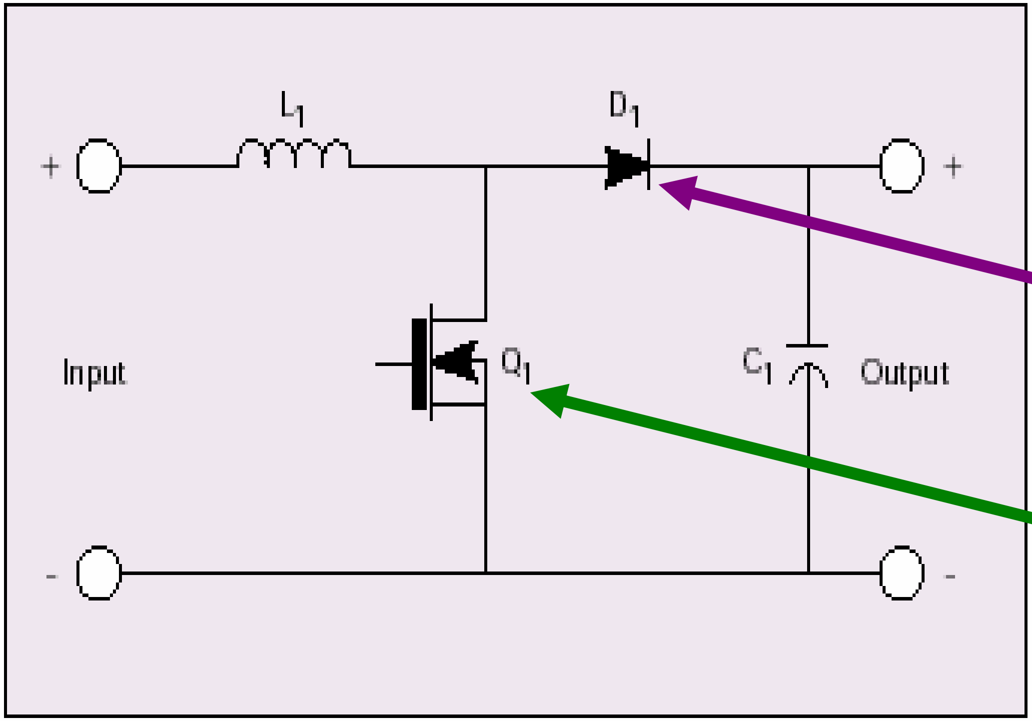
$$\boxed{I_o = \frac{1}{2} I_{L\max} \frac{T_{off}}{T_S} = \frac{D^2}{2 L f_S} \frac{{V_{in}}^2}{V_o - V_{in}}}$$

Boost

Disadvantages: a limited power range a relatively high output ripple due to all of the off-time energy coming from the output capacitor

Advantages: simplicity, low cost and the ability to achieve up conversion without a transformer

Useful Power Level: 1 to 50 W
Switch Voltage Stress: V_{out}
Switch Power Stress: P_{in}
Transformer Utilization: N/A
Duty Cycle: <1.0
Output Ripple Frequency: f_S
Relative Cost: Low



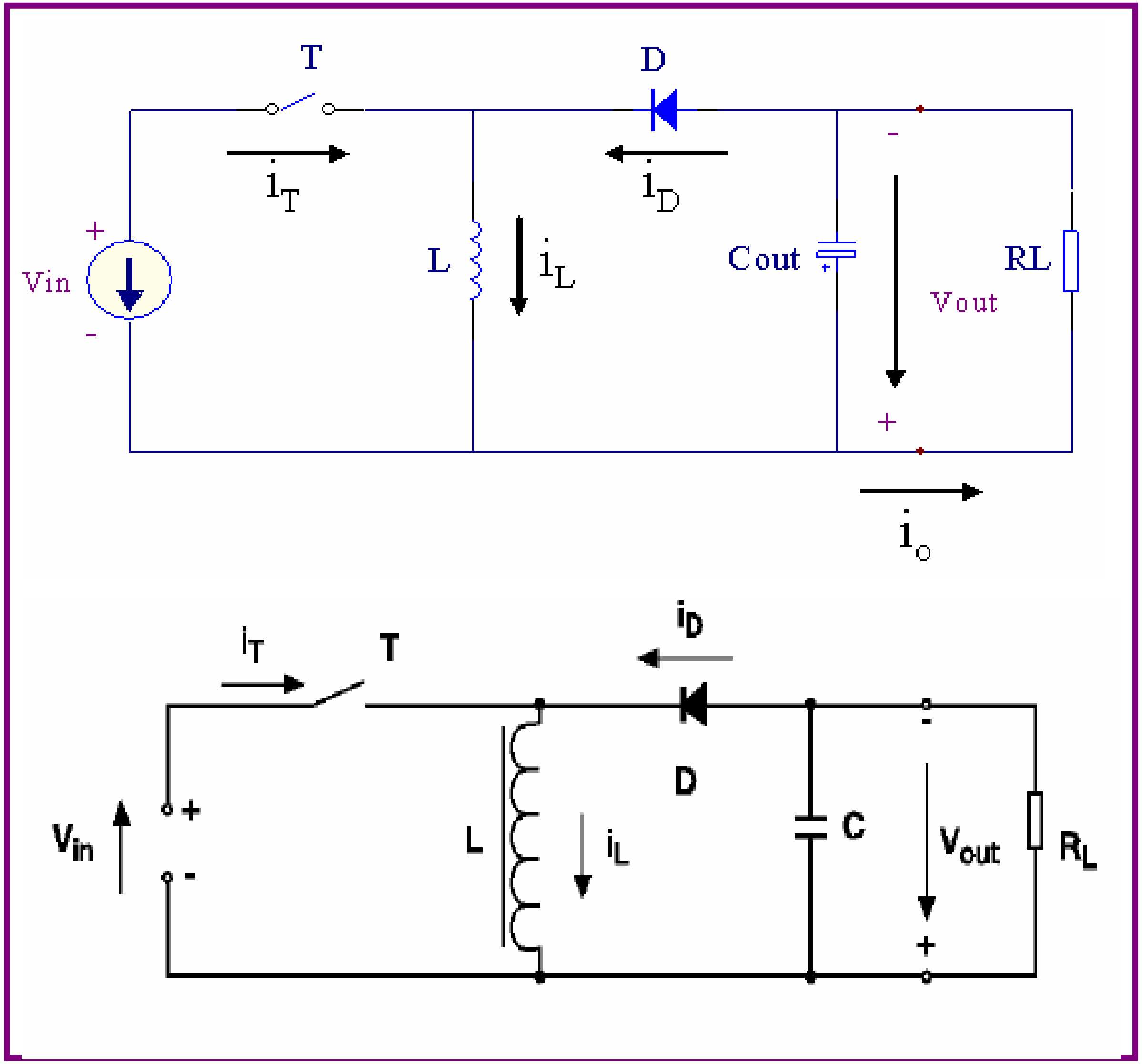
Rectifier:
$V_{RRM} > V_o$ $I_{F(AV)} > I_o$

Power Switch:
$V_{DDS} > V_o$ $I_{Dmax} > I_o/(1-D)+\Delta I/2$

$f_S = 1/T_S$ $D = T_{on}/T_S$ $V_o = V_{in}/(1-D)$

3 The Buck-Boost Converter

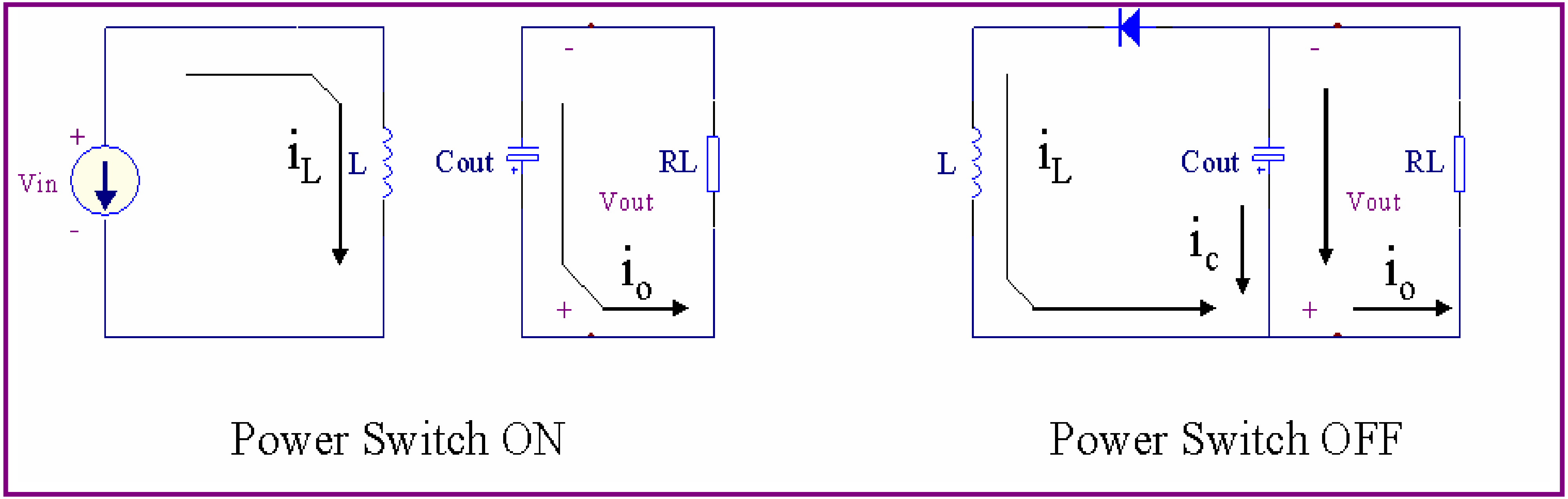
Buck-Boost



Buck-Boost
Converter

Step down-up Voltage
Regulator

Buck-Boost



Power Switch ON

Power Switch OFF

State 1: S is on, the inductor current rises linearly:

$$L\frac{di_L}{dt} = V_{in} \qquad \Delta I_{pk} = \frac{V_{in}D}{Lf_S}$$

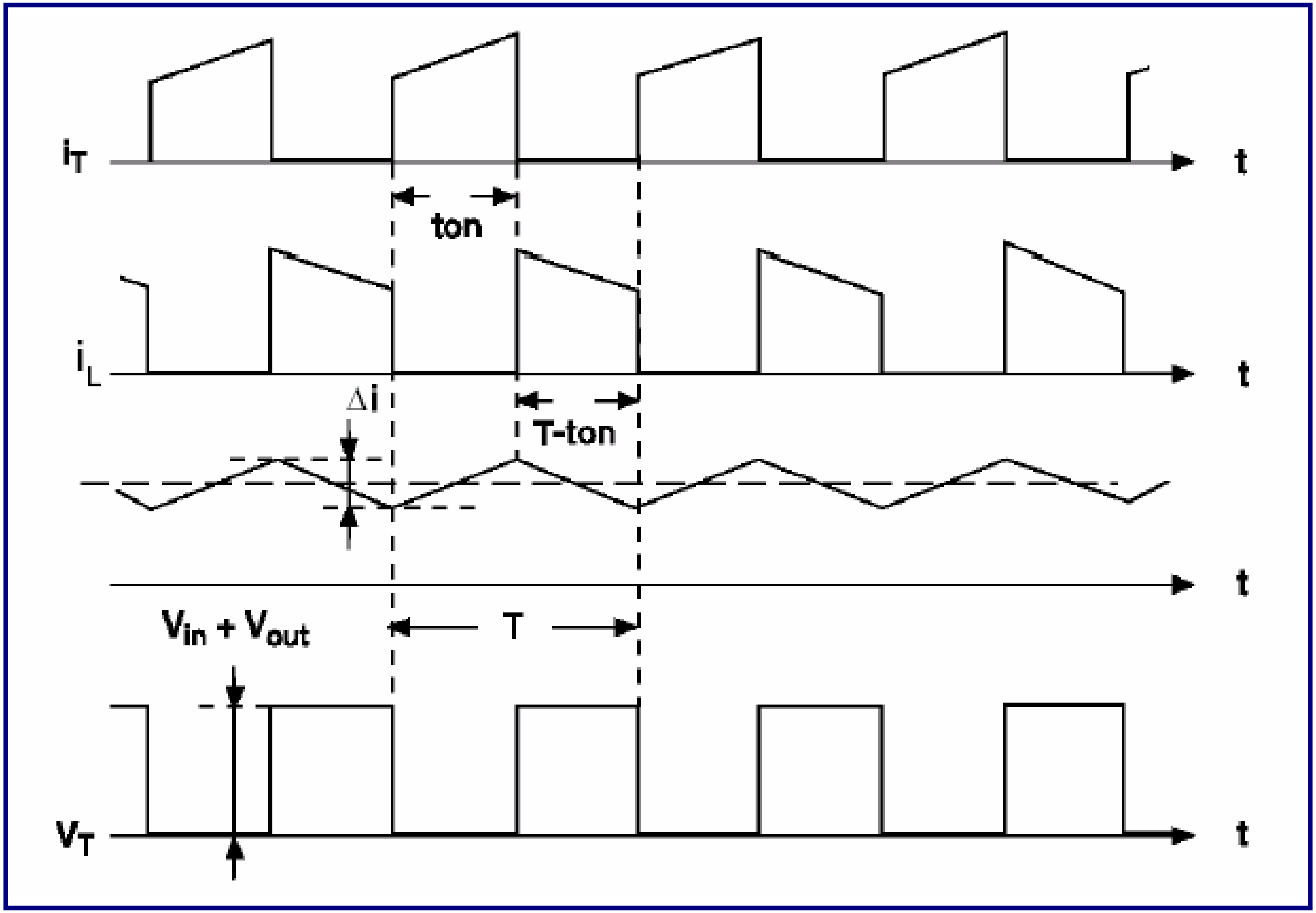
State 2: S is off, the inductor current decreases linearly:

$$-L\frac{di_L}{dt} = V_o \qquad \Delta I_{pk} = \frac{V_o(1-D)}{Lf_S}$$

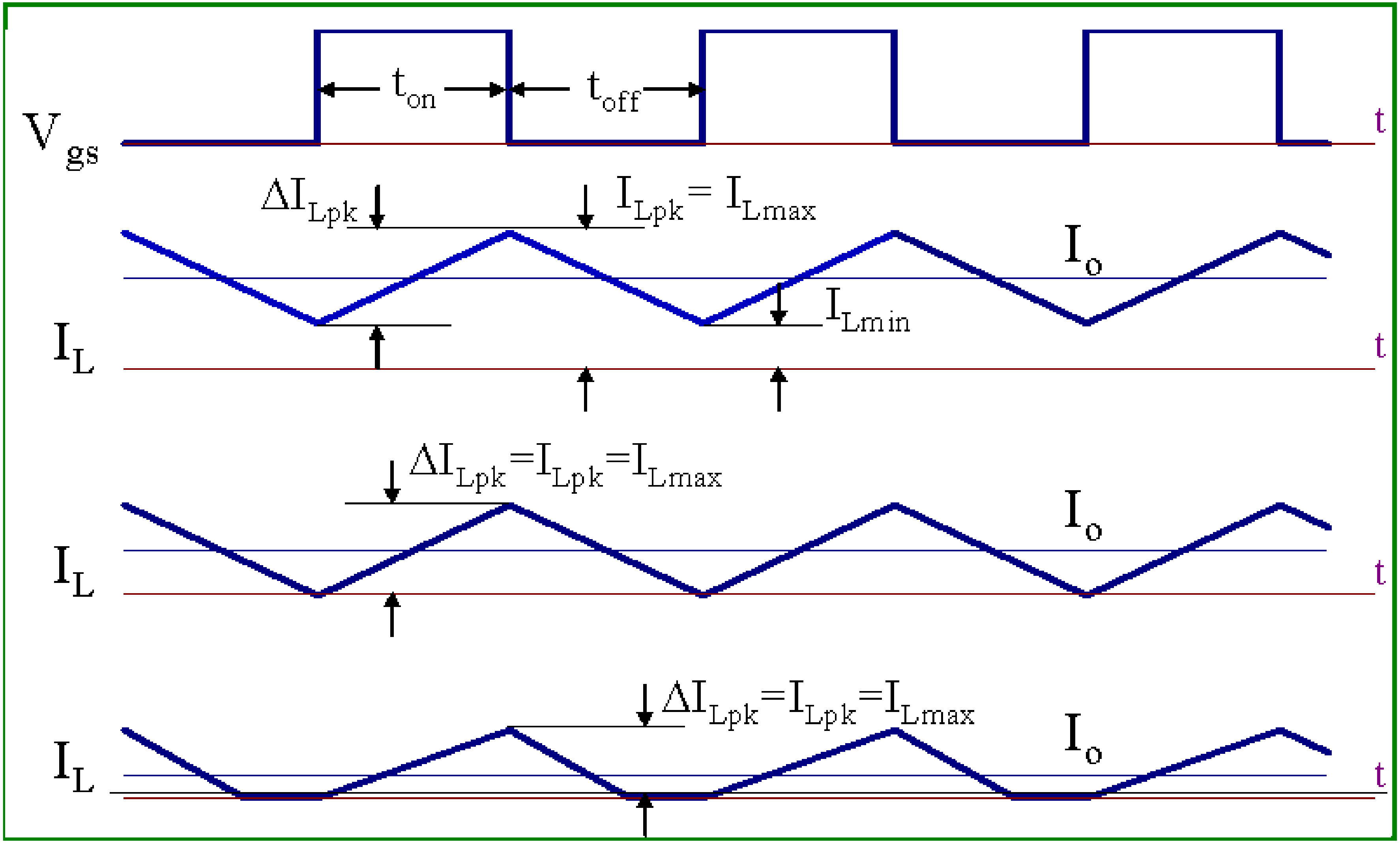
Volts Second Balance: $V_o = V_{in}D/(1\text{-}D)$, $D = T_{on}/ T$

$V_{in} \cdot I_{in} = V_o \cdot I_o$, $I_{in} = I_o\,(1\text{-}D)/D$

Buck-Boost



Buck-Boost



V_{gs}
t_{on}
t_{off}
t
ΔI_{Lpk}
$I_{Lpk} = I_{Lmax}$
I_o
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I_L
t
$\Delta I_{Lpk}=I_{Lpk}=I_{Lmax}$
I_o
I_L
t
$\Delta I_{Lpk}=I_{Lpk}=I_{Lmax}$
I_o
I_L
t

Buck-Boost

Critical condition between DCM and CCM

$$I_{in} = \frac{1}{2} I_{L\max} = \frac{V_{in} D}{2 L_f f_S}$$

DCM

$$I_{in} < \frac{1}{2} I_{L\max} = \frac{V_{in} D}{2 L_f f_S}$$

$$T_{off} = D' T_S = \frac{V_{in} D}{V_o} T_S < (1 - D) T_S$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{D}{D'}}$$

Power Balance

Volts-Sec Balance

$$\boxed{I_o = \frac{1}{2} I_{L\max} \frac{T_{off}}{T_S} = \frac{D^2}{2 L f_S} \frac{V_{in}^2}{V_o}}$$

Buck-Boost

DCM

$$P_{in} = \frac{1}{2} L I_{L\,pk}{}^{2} f_S \qquad I_{Lpk} = \sqrt{\frac{2P_{in}}{Lf_S}}$$

$D=T_{on}/T_S$

$D_2=T_{off}/T_S$

$T_S=T_{on}+T_{off}+T_{off1}$

$$D = \frac{1}{V_{in}} \sqrt{2P_{in} L f_S}$$

$$D_2 = \frac{1}{V_o} \sqrt{2P_{in} L f_S} \quad \Longrightarrow \quad L_o \le \frac{1}{2P_{\max} f_S \left(\frac{1}{V_{in\min}} + \frac{1}{V_o}\right)^2}$$

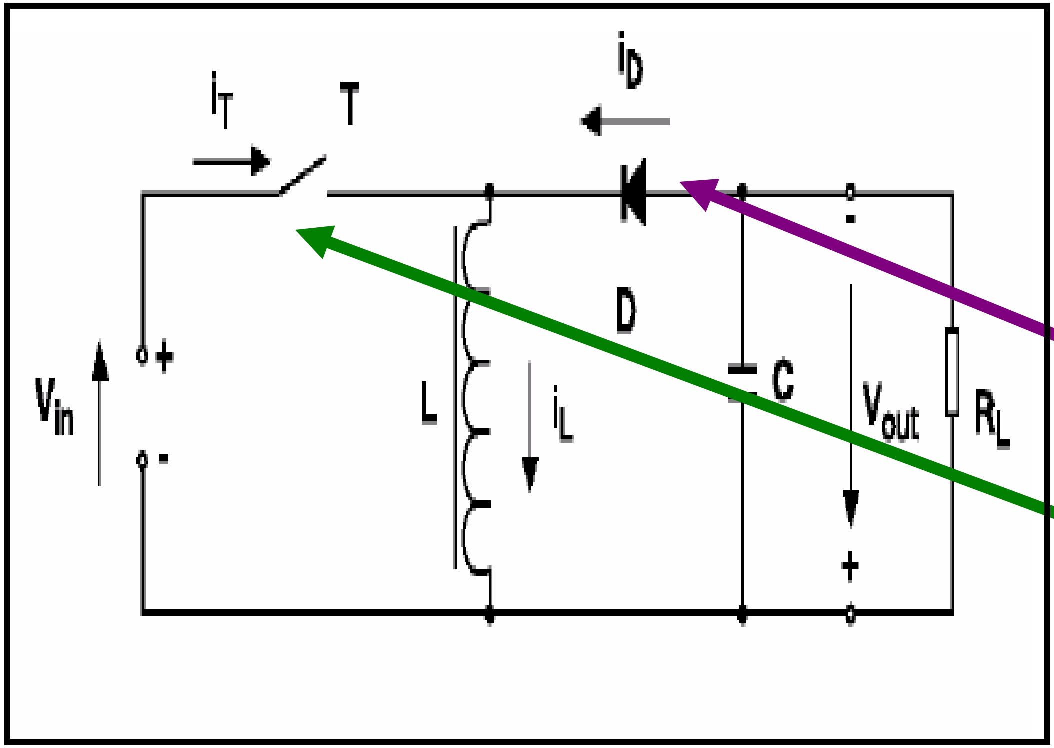
$$D_{\max} + D_{2\max} \le 1$$

Buck-Boost

Disadvantages: a limited power range a relatively high output ripple due to all of the off-time energy coming from the output capacitor

Advantages: simplicity, low cost and the ability to achieve negative conversion without a transformer

Useful Power Level: 1 to 50 W
Switch Voltage Stress: $V_{inmax} + V_{out}$
Switch Power Stress: P_{in}
Transformer Utilization: N/A
Duty Cycle: <1.0
Output Ripple Frequency: f_S
Relative Cost: Low



Rectifier:

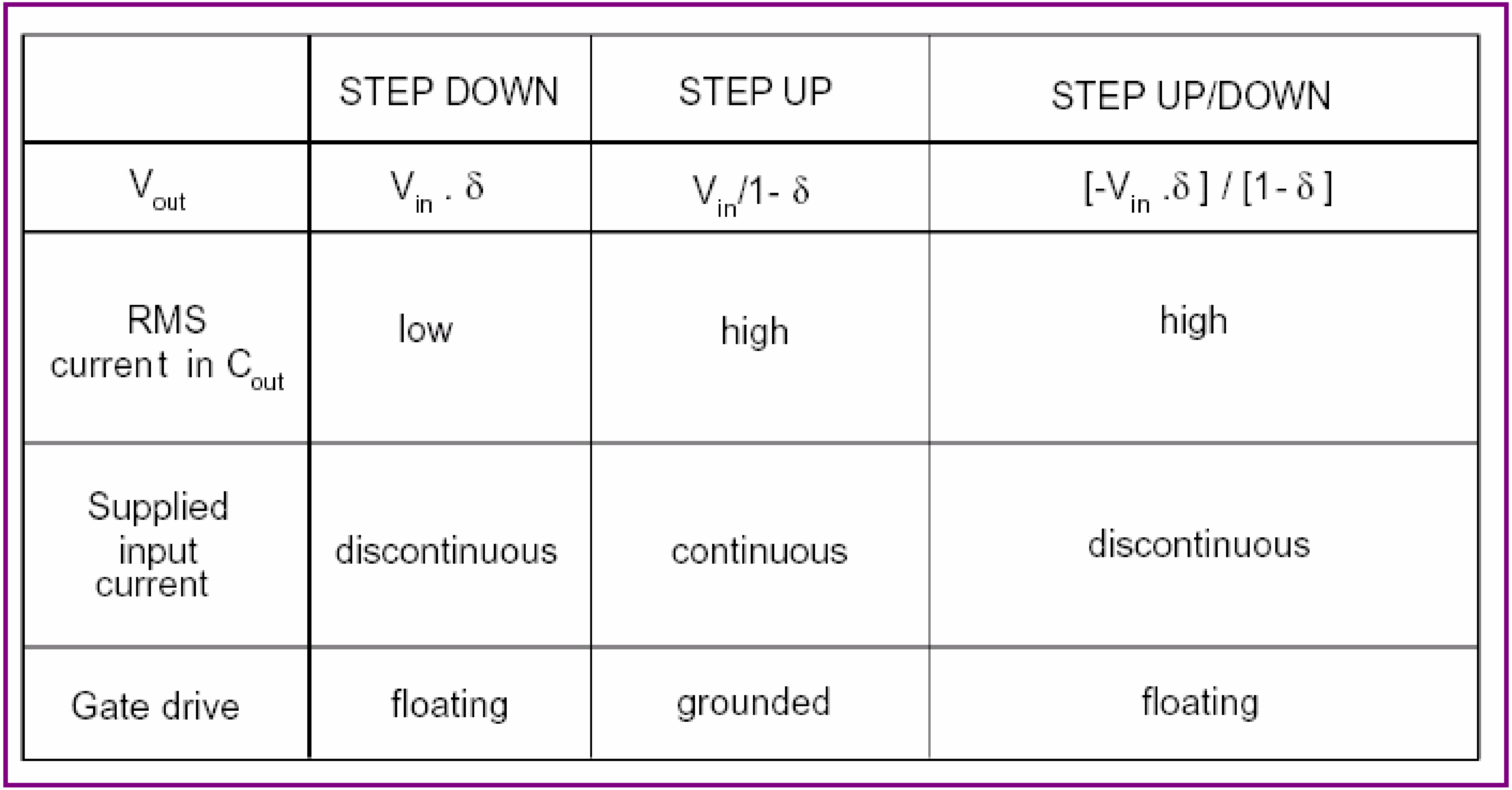
$V_{RRM} > V_{inmax} + V_o$ $I_{F(AV)} > I_o$

Power Switch:

$V_{DDS} > V_{inmax} + V_o$ $I_{Dmax} > I_o/(1-D) + \Delta I/2$

$f_S = 1/T_S$ $D = T_{on}/T_S$ $V_o = V_{in}/(1-D)$

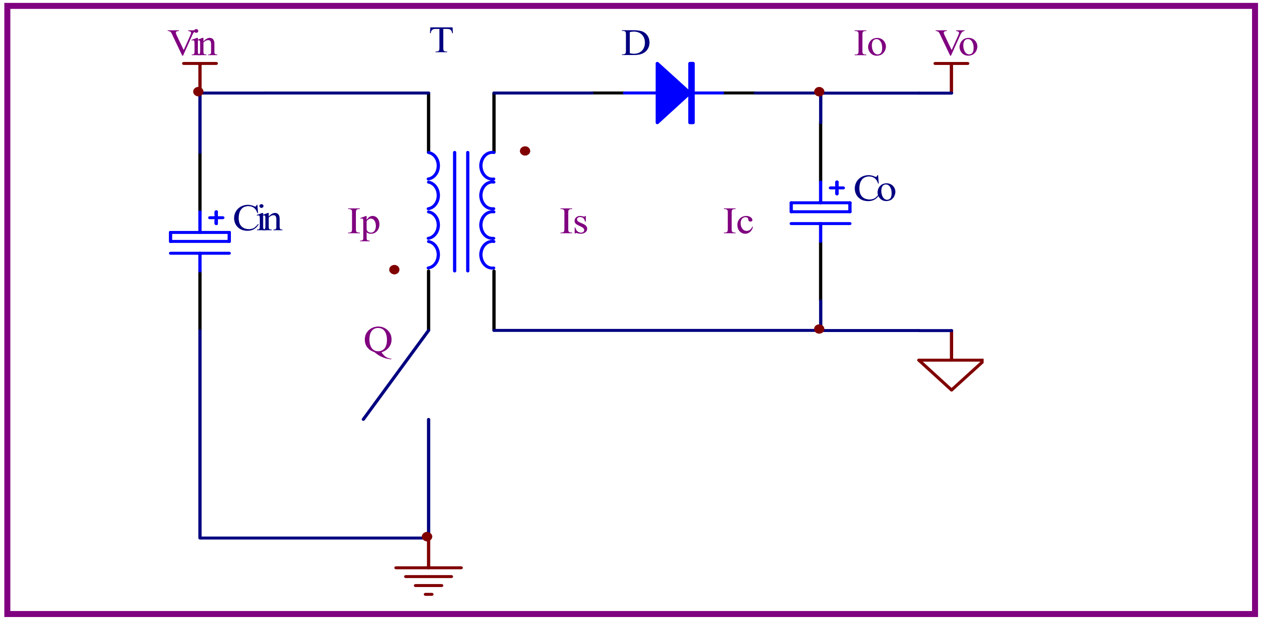
Conclusion



	STEP DOWN	STEP UP	STEP UP/DOWN
V_{out}	$V_{in} . \delta$	$V_{in}/1- \delta$	$[-V_{in} .\delta] / [1- \delta]$
RMS current in C_{out}	low	high	high
Supplied input current	discontinuous	continuous	discontinuous
Gate drive	floating	grounded	floating

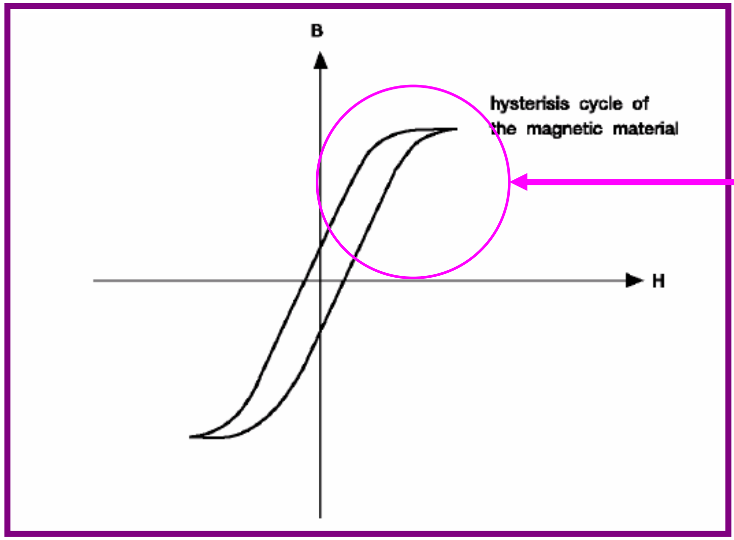
3 The Fly Back Converter

Fly Back



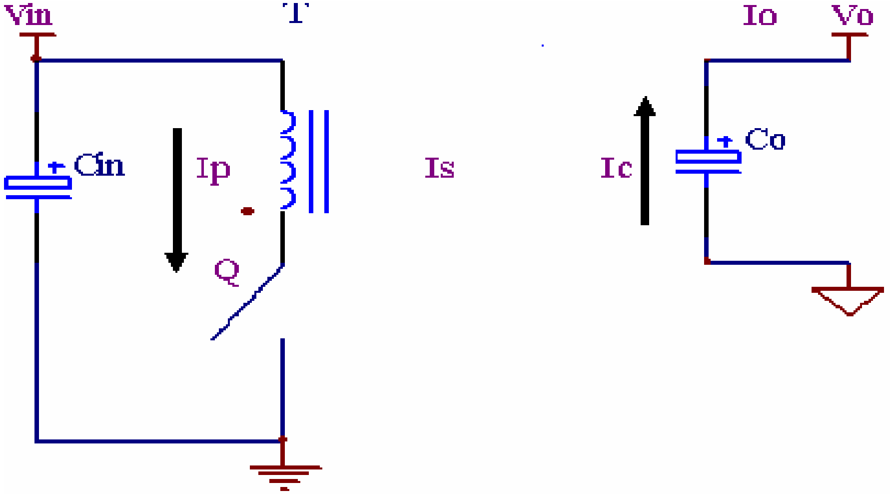
Fly Back
Converter

It is derivate from
the Buck-Boost

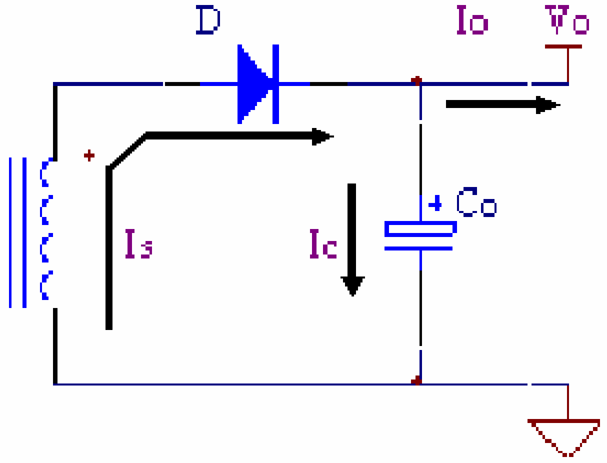


Single End
Converter

Fly Back



Power Switch ON



Power Switch OFF

State 1: S is on, the inductor current ramps up linearly:

$$L\frac{di_L}{dt} = V_{in} \qquad \Delta I_{pk} = \frac{V_{in}D}{Lf_S}$$

State 2: S is off, the inductor current decreases linearly:

$$-L\frac{di_L}{dt} = nV_o \qquad \Delta I_{pk} = \frac{nV_o(1-D)}{Lf_S}$$

Volts Second Balance: $V_o = V_{in}D/n(1\text{-}D)$, $D = T_{on}/T$, $n = N_p/N_s$

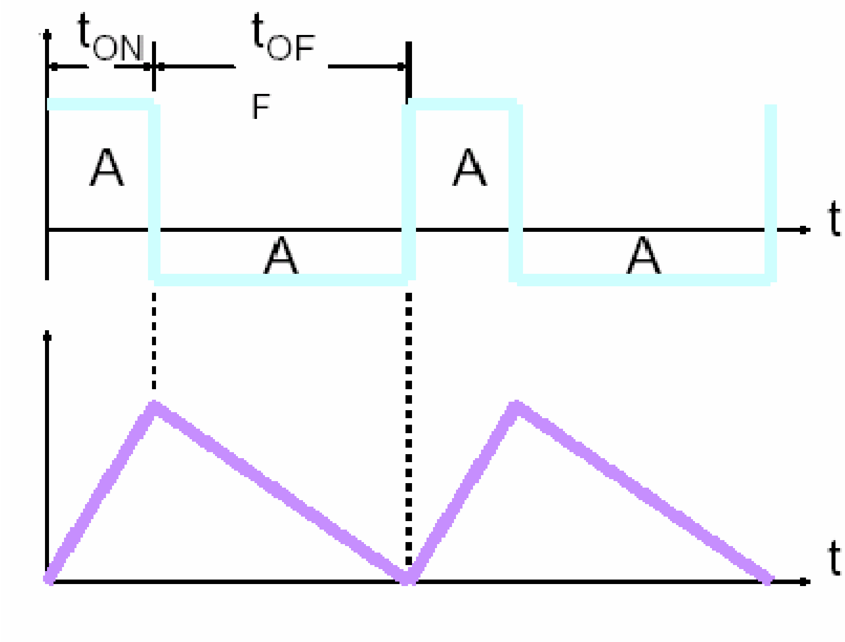
$V_{in} \cdot I_{in} = V_o \cdot I_o$, $I_{in} = I_o\,(1\text{-}D)/D$

Fly Back

Volt-Second Balance

The net change in energy in the transformer must be zero over one cycle.

The volt-seconds across the primary during turn on must equal that across the secondary during turn off, reflected to the primary.



$$(V_{in}-V_{DSS})T_{on} = V_{fl}T_{off}$$

$$V_{fl} = nV_o$$

$$n = N_p/N_s$$

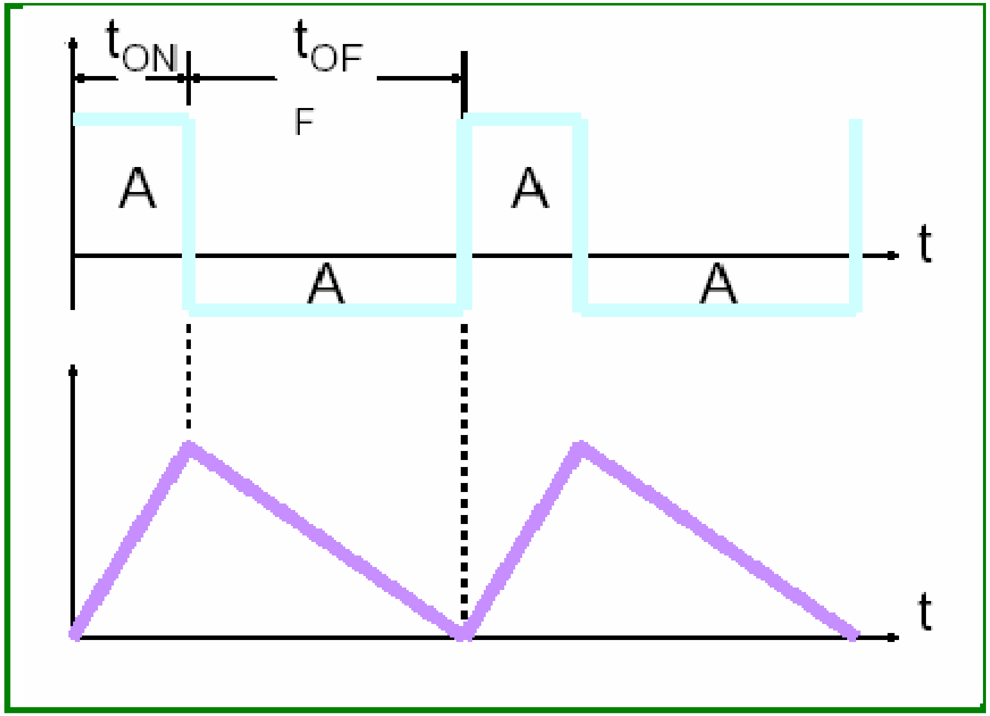
$$V_{DSS} = 0$$

Fly Back

Volt-Second Balance

The net change in energy in the inductor must be Zero (average voltage: 0) over one cycle.

The integral of voltage over time volt-seconds across the inductor during turn on must equal that across the secondary during turn off

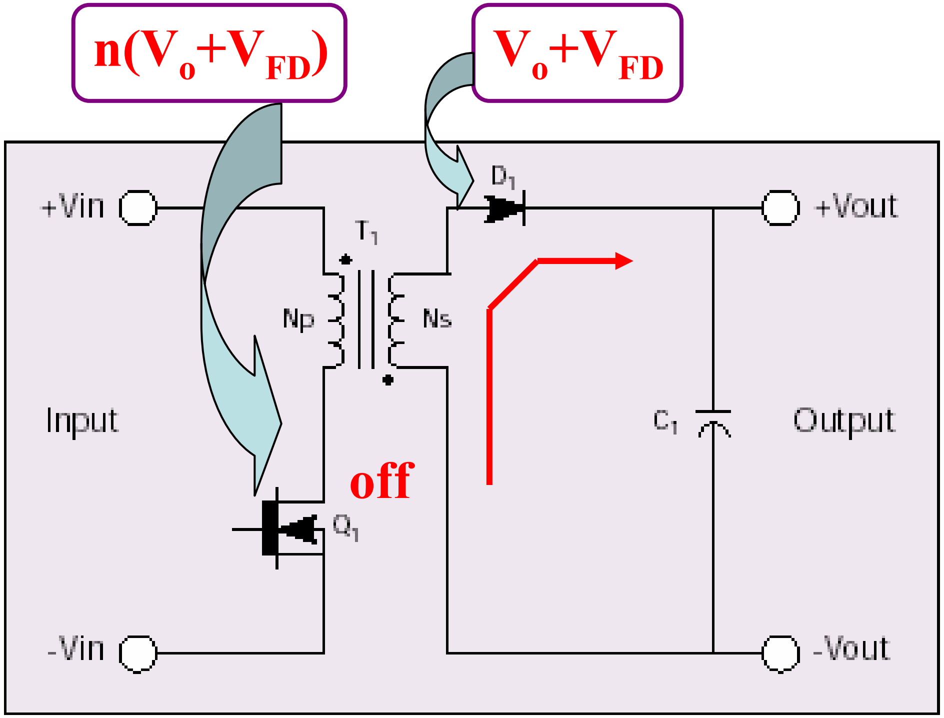


$$V_{Lon}T_{on} = V_{Loff}T_{off}$$

The change in current ΔI must be constant:

$L\Delta I = V\,\Delta t$

Fly Back



Reflected Voltage During Off Stage

The approximate voltage across the secondary winding reflected to the primary

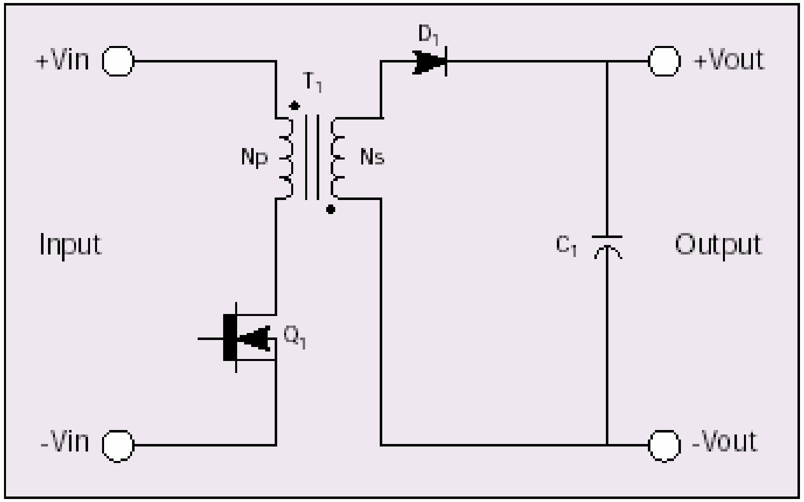
$$V_{fl} = n(V_o+V_{FD})$$
$$= nV_o$$

$$n = N_p/N_s$$

V_{FD}: the forward voltage drop across the freewheeling diode

The reflected voltage is dependent on turns ratio and output voltage

Fly Back



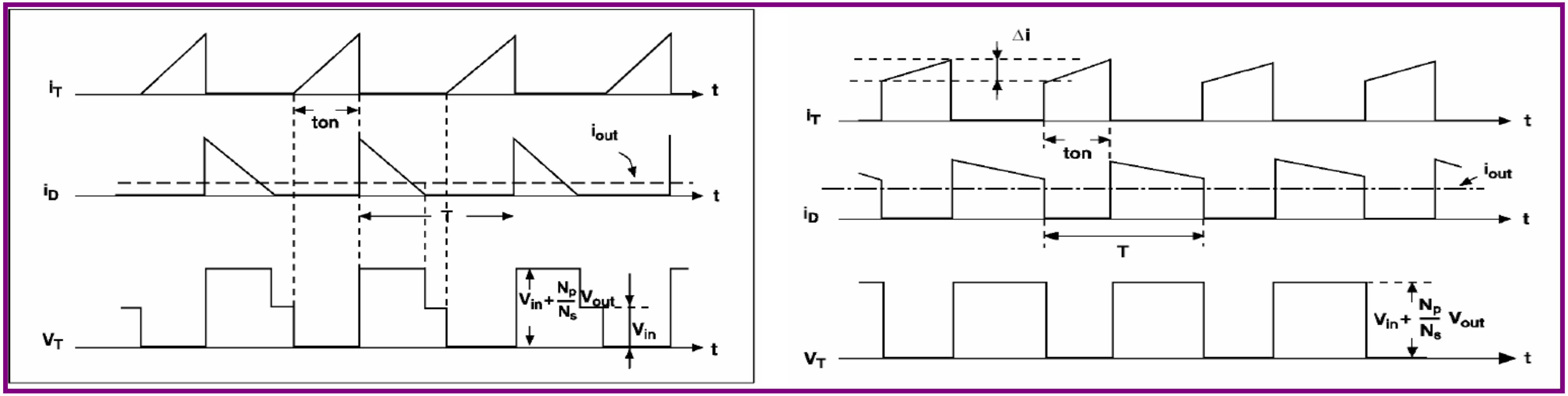
Operation Modes for constant frequency fly back converter

①**CCM**--continuous

②**DCM**--discontinuous

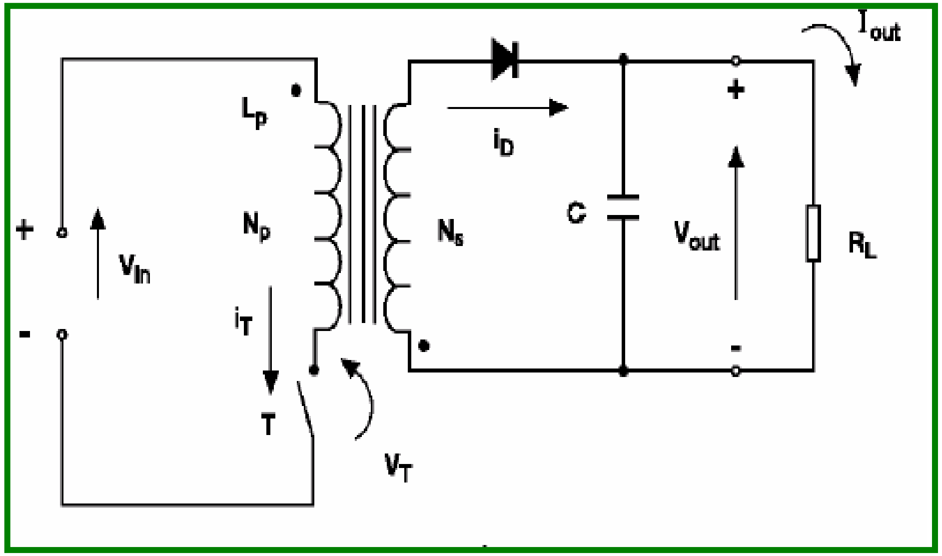
The variable frequency or the self oscillating fly back converter

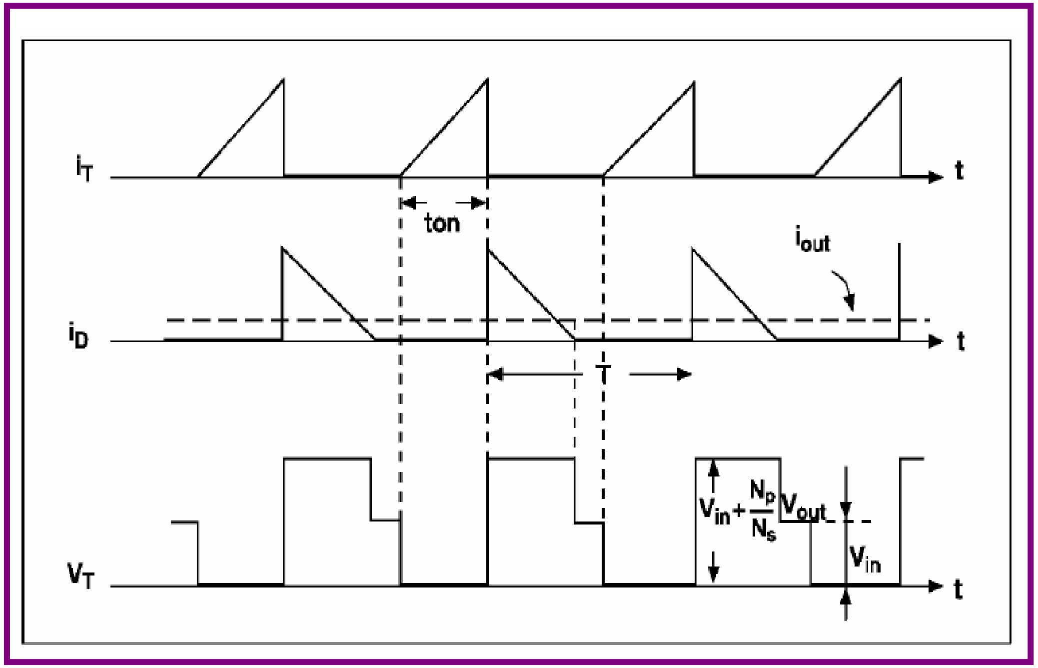
Ring Choke Converter operates at Critical Discontinuous Converter



Fly Back

DCM





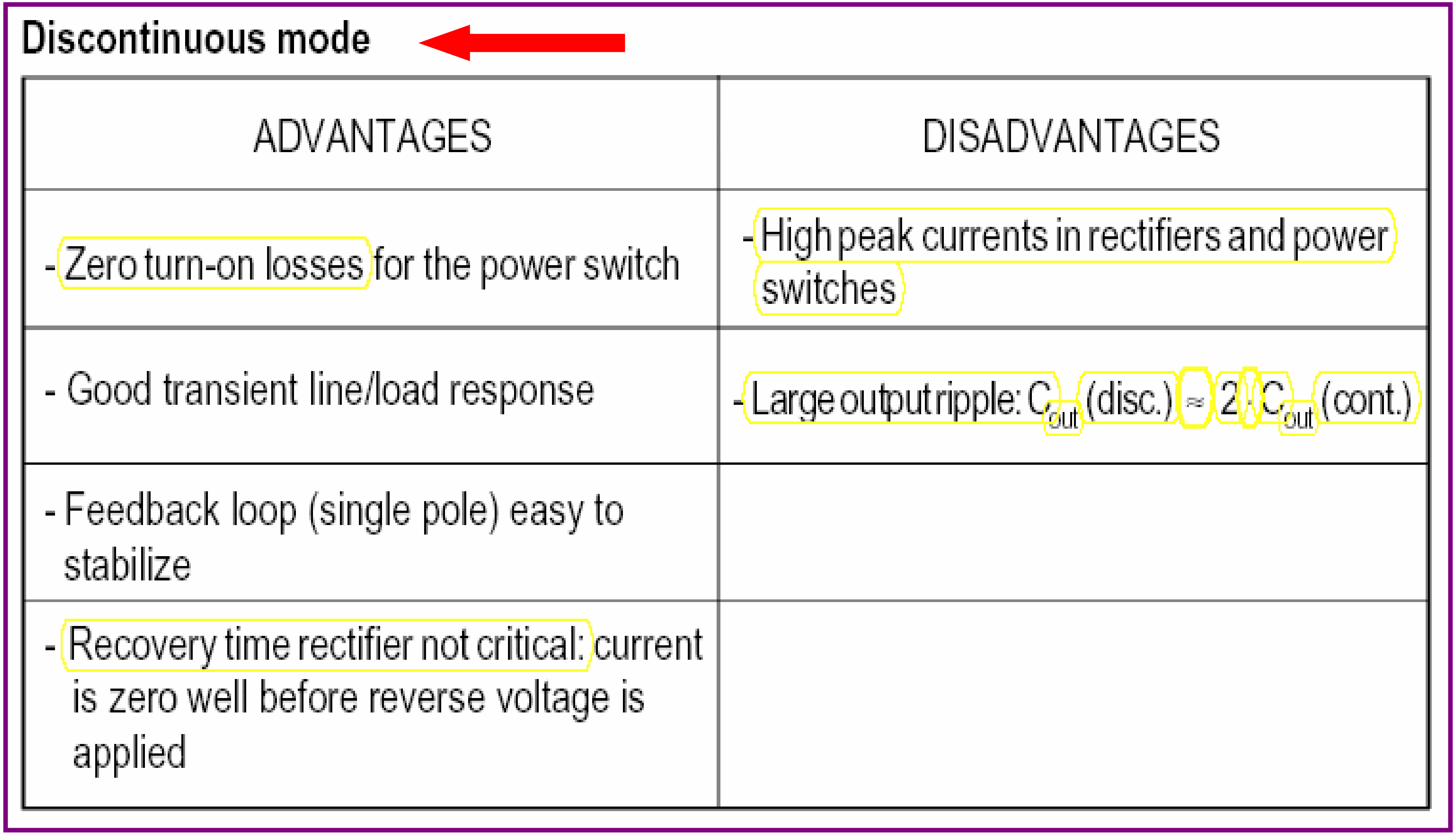
Power Switch: $V_{DDS} > V_{inmax} + nV_o$ + leakage inductance spike

$$I_{Dpeak} > \frac{2P_{in}}{D_{\max} V_{in\min}} \qquad I_{Drms} > \frac{2P_{in}}{V_{in\min}} \sqrt{\frac{1}{3D_{\max}}}$$

Secondary rectifier: $V_{RRM} > V_o + V_{inmax}/n$

$$I_{Fpeak} > \frac{2P_o}{V_o(1-D_{\max})} \qquad I_{F(AV)} > \frac{P_o}{V_o}$$

Fly Back

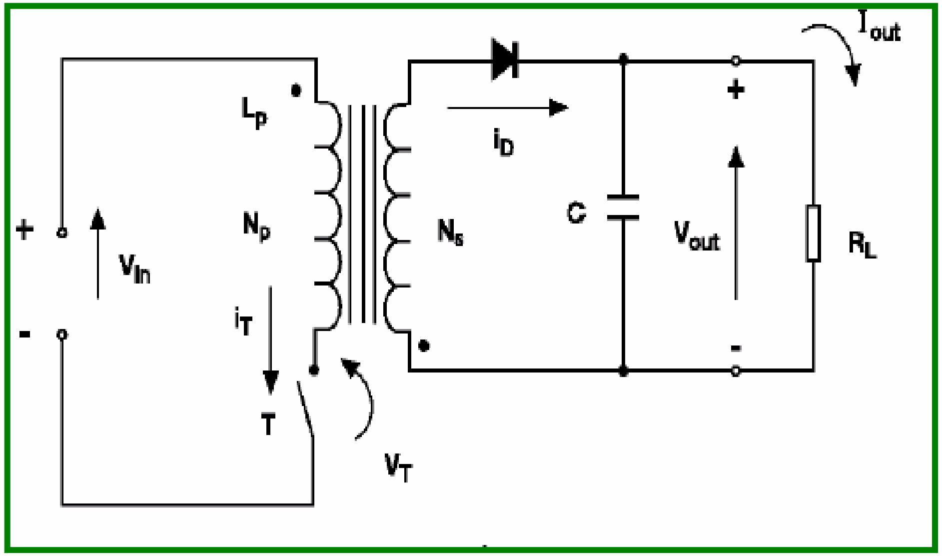


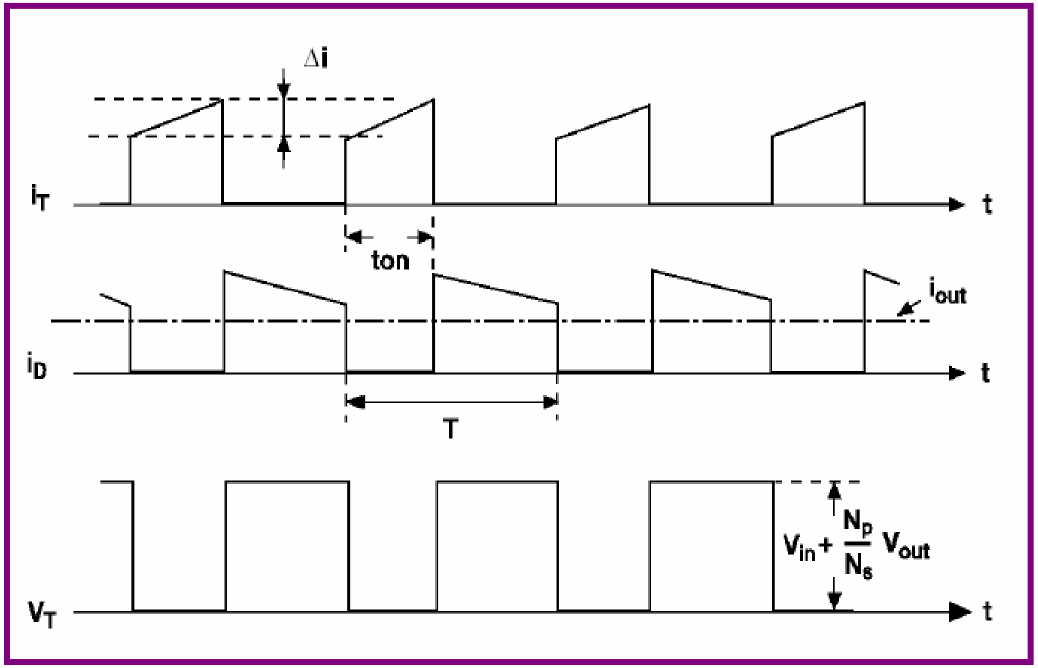
Discontinuous mode

ADVANTAGES	DISADVANTAGES
- Zero turn-on losses for the power switch	- High peak currents in rectifiers and power switches
- Good transient line/load response	- Large output ripple: C_{out} (disc.) $\approx 2 \cdot C_{out}$ (cont.)
- Feedback loop (single pole) easy to stabilize	
- Recovery time rectifier not critical: current is zero well before reverse voltage is applied	

Fly Back

CCM





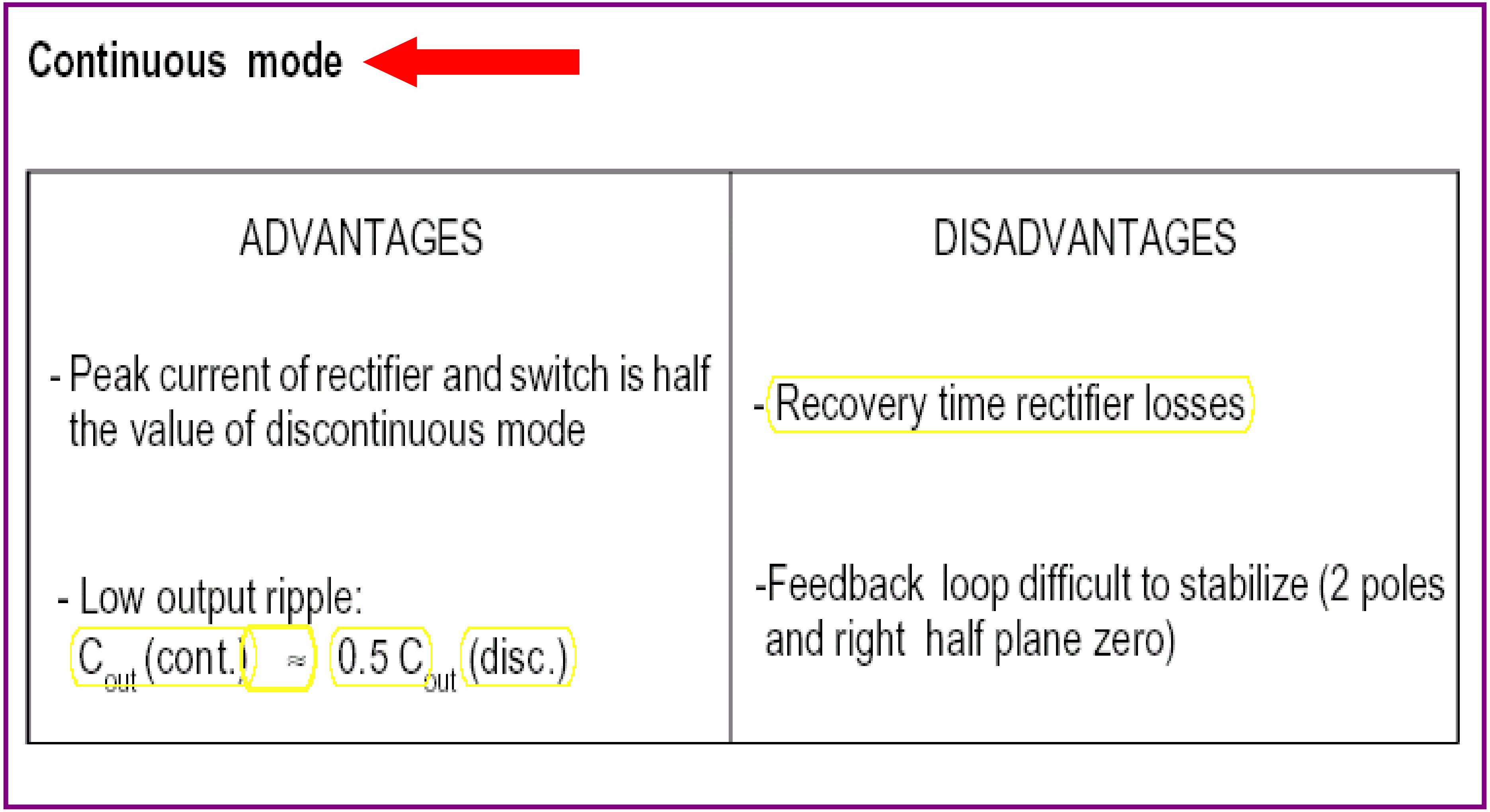
Power Switch: $V_{DDS} > V_{inmax} + nV_o$ + leakage inductance spike

$$I_{Dpeak} > \frac{2P_{in}}{D_{\max} V_{in\min}(1+A)} \qquad I_{Drms} > \frac{2P_{in}}{V_{in\min}}\sqrt{\frac{1+A+A^2}{3D_{\max}}}$$

Secondary rectifier: $V_{RRM} > V_o + V_{inmax}/n$

$$I_{Fpeak} > \frac{2P_o}{V_o(1-D_{\max})(1+A)} \qquad I_{F(AV)} > \frac{P_o}{V_o} \qquad A = \frac{I_{peak} - \Delta I}{I_{peak}} = \frac{I_{\min}}{I_{peak}}$$

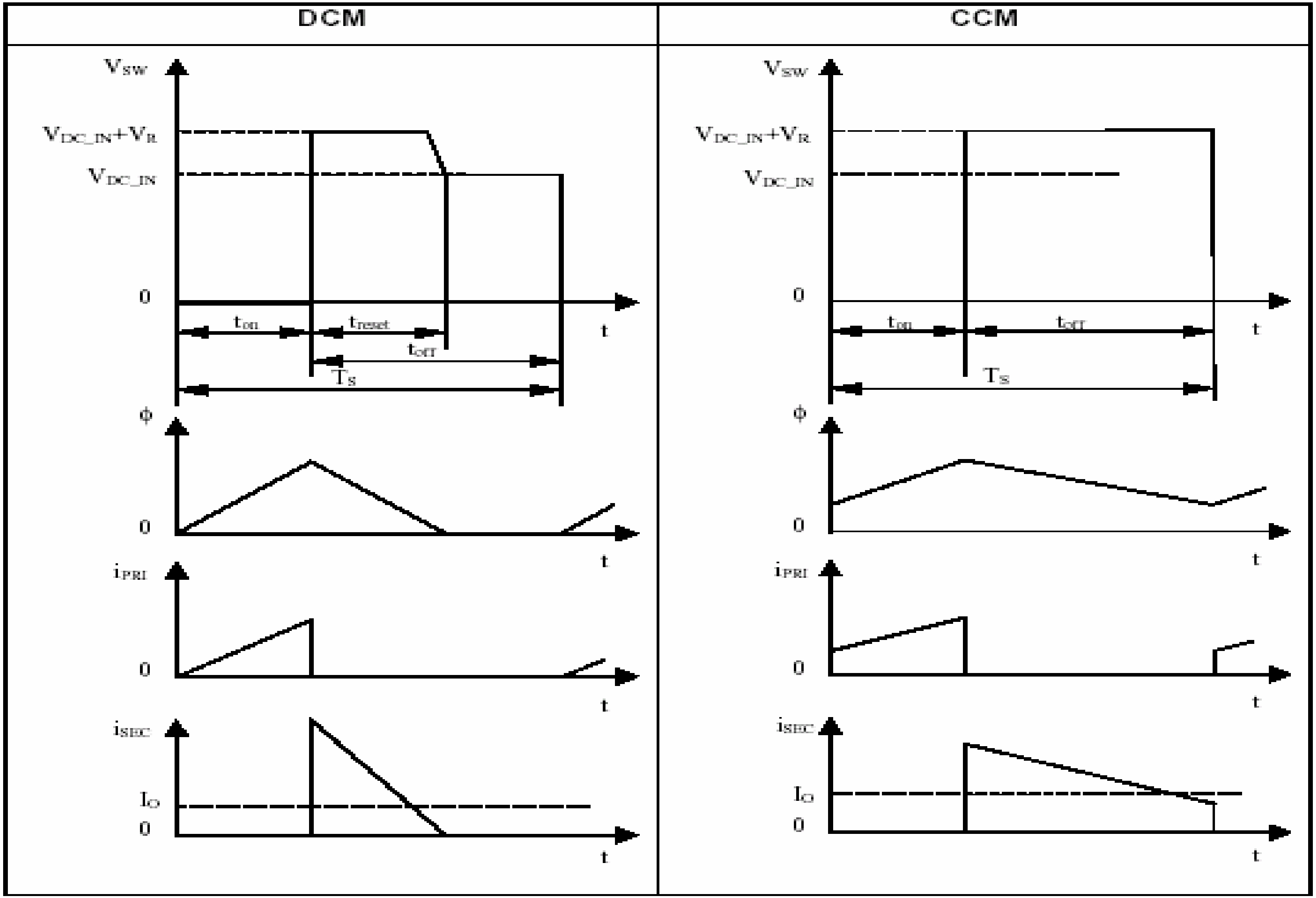
Fly Back



Continuous mode

ADVANTAGES	DISADVANTAGES
- Peak current of rectifier and switch is half the value of discontinuous mode	- Recovery time rectifier losses
- Low output ripple: $C_{out}(\text{cont.}) \approx 0.5\, C_{out}(\text{disc.})$	-Feedback loop difficult to stabilize (2 poles and right half plane zero)

Fly Back



Fly Back

Advantages

DCM

①More rapid response
②No right half plane pole and easy to compensate for feedback
③A slow recovery secondary diode can be used

CCM

①Lower rating required due to lower peak current
②Lower transient output voltage
③Spike at turn off

Disadvantages

DCM

①High capacitor ripple current
②High peak diode current
③Higher mosfet current

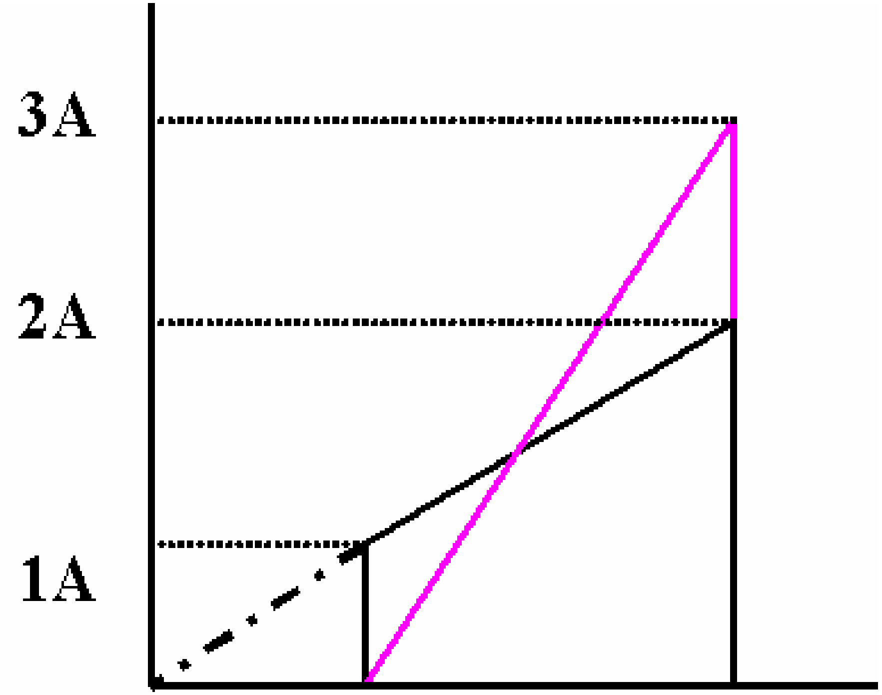
CCM

①Needs bigger transformer
②Commutating the secondary diode can cause switching noise around the output diode and ring in the ransformer
can give worse EMI results

Fly Back

Given the same current excursion ΔI, larger throughout power if provided by continuous mode

For the same output power, peak currents are higher during discontinuous mode



The energy stored in the primary winding during turn on is given by:

$$E_{stored} = L_p I_{ppk}^2/2$$

The throughout power going into the primary winding is:

$$P_{in} = L_p f(I_{pmax}^2 - I_{pmin}^2)/2$$

The energy and power delivered by the secondary are:

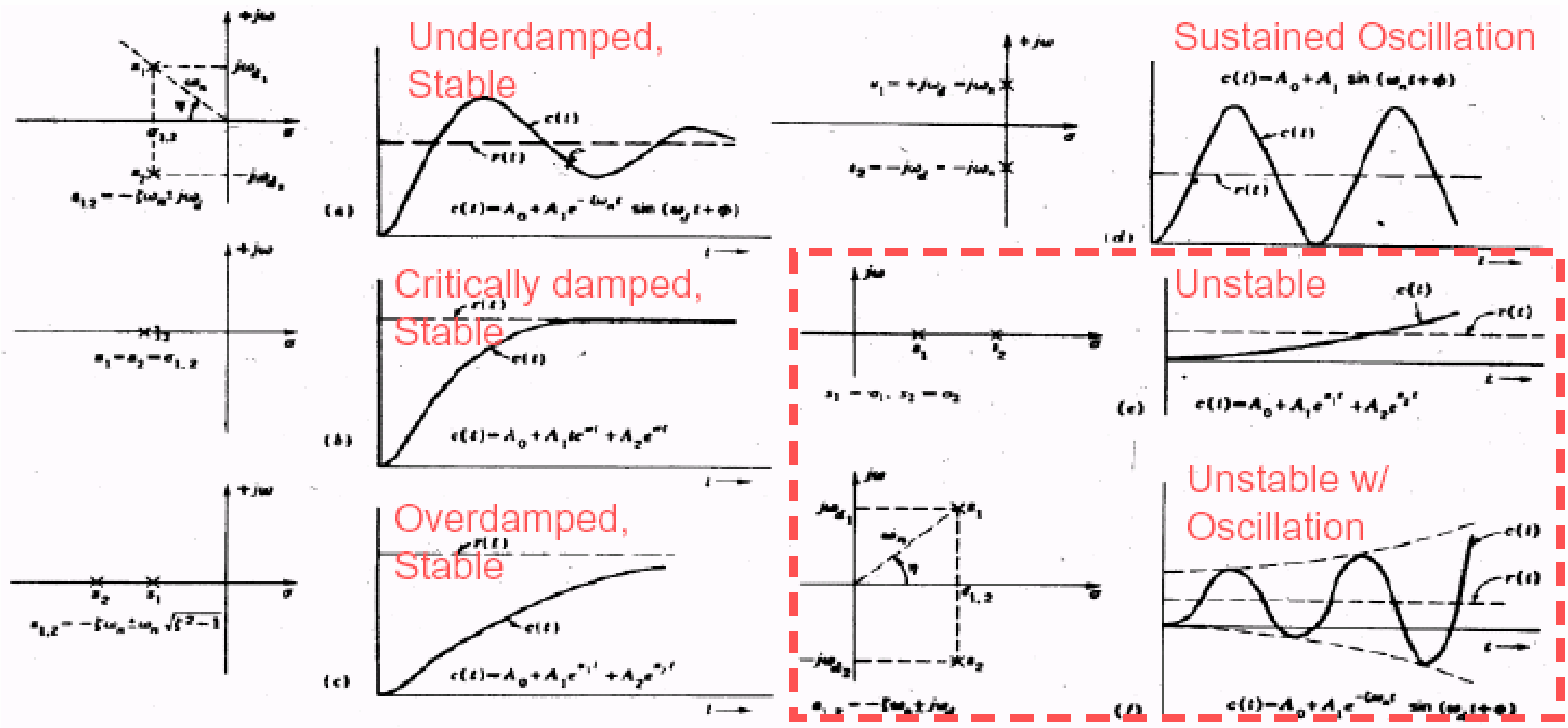
$$E_{delivered} = L_s I_{spk}^2/2$$

$$P_o = L_s f(I_{smax}^2 - I_{smin}^2)/2$$

$$P_{in} = P_o,\ E_{stored} = E_{delivered}$$

Fly Back

Right Half Plane Zero



- Right half plane zeroes in the characteristic equation {1 + G(s)H(s)} tends to destabilize the system.

Fly Back

Critically discontinuous operation

It is the transition point between DCM and CCM. With critically discontinuous mode of operation, primary winding current starts from zero at every cycle. Secondary current goes down to zero just when primary winding current starts ramping up again.

Off time + on time = fly back period

There is no idle period. Equation for DCM can apply for it.

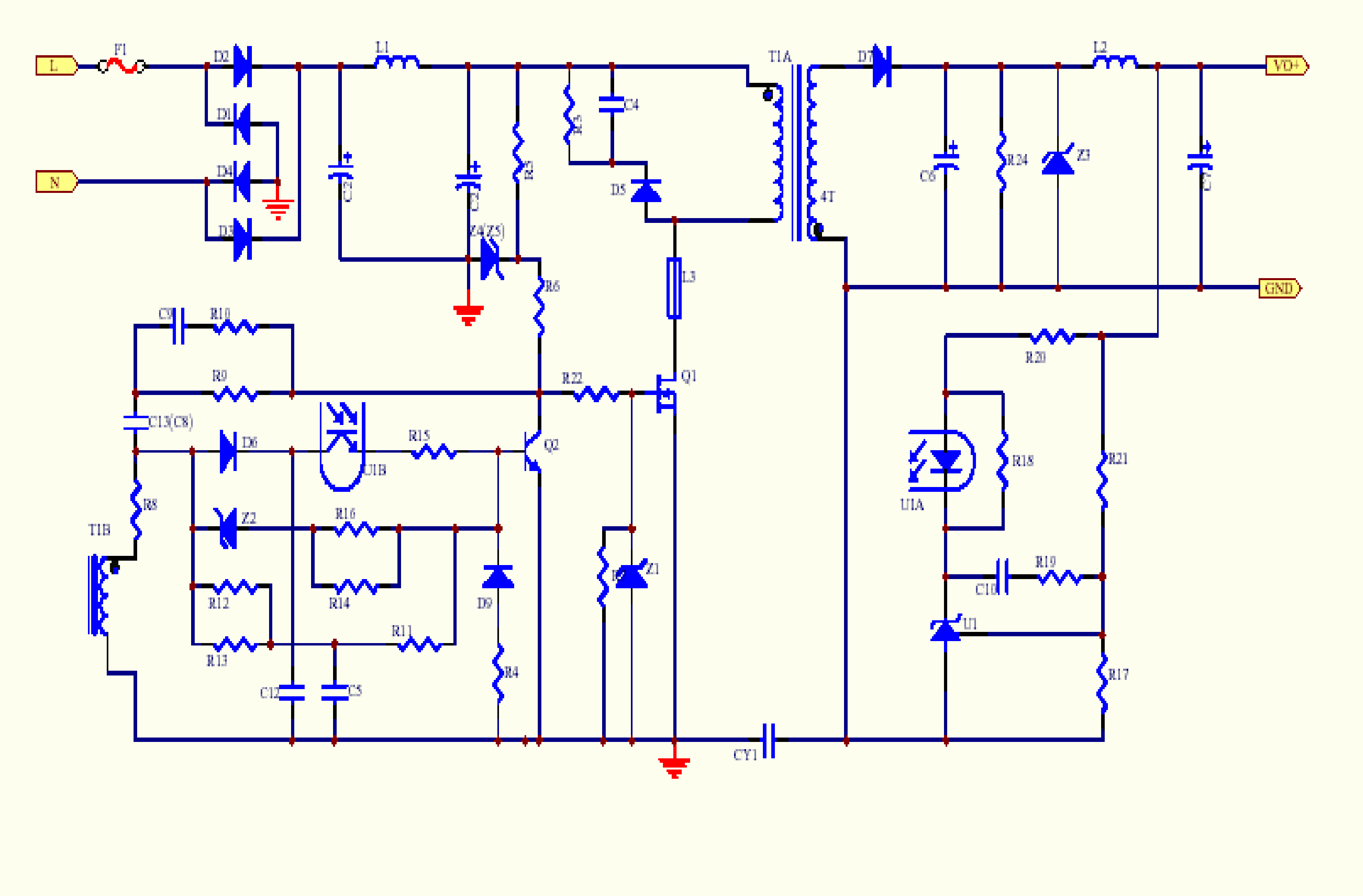
Given a constant turn on period, output current is a function of turn off period. The rule of thumb for 50% duty cycle, you have to transfer twice th total output power within the on period.

Po = LfIpk2/2

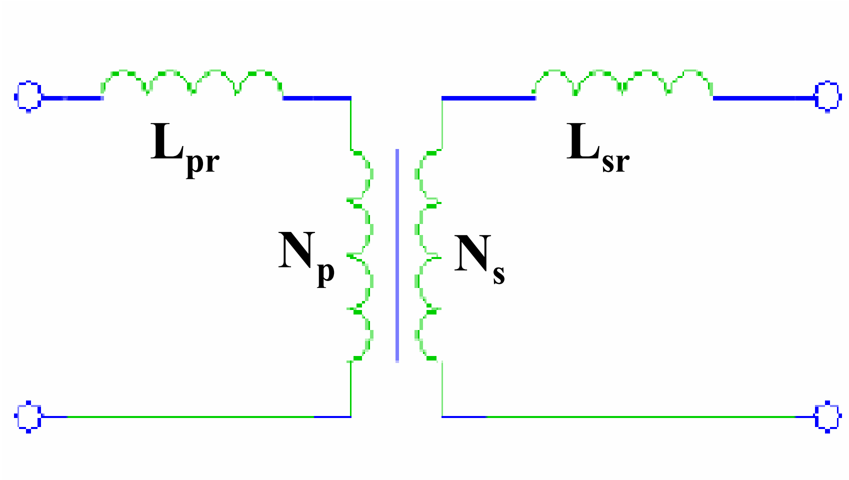
For ¼ the original power, frequency will double. At no load frequency will go very very high so a minimum and maximum load must be determined.

Fly Back

RCC

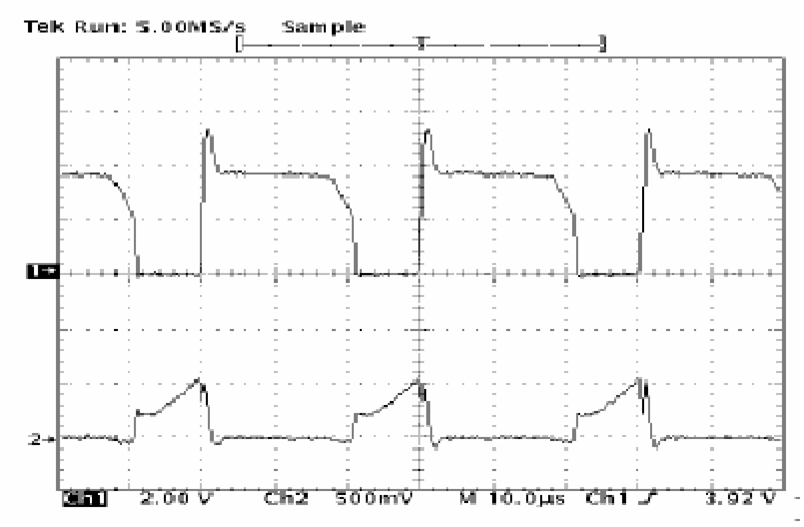

L
F1
D2
L1
T1A
D7
L2
VO+
D1
C4
R5
R3
Z3
R24
N
D4
C3
C2
D5
C6
C1
4T
D3
Z4(Z5)
L3
GND
R6
C9
R10
R20
R9
R22
Q1
C13(C8)
D6
U1B
R15
Q2
R18
R21
U1A
R8
Z2
R16
T1B
Z1
R19
C10
D9
R12
R14
R11
U1
R13
R4
C12
C5
R17
CY1

Fly Back



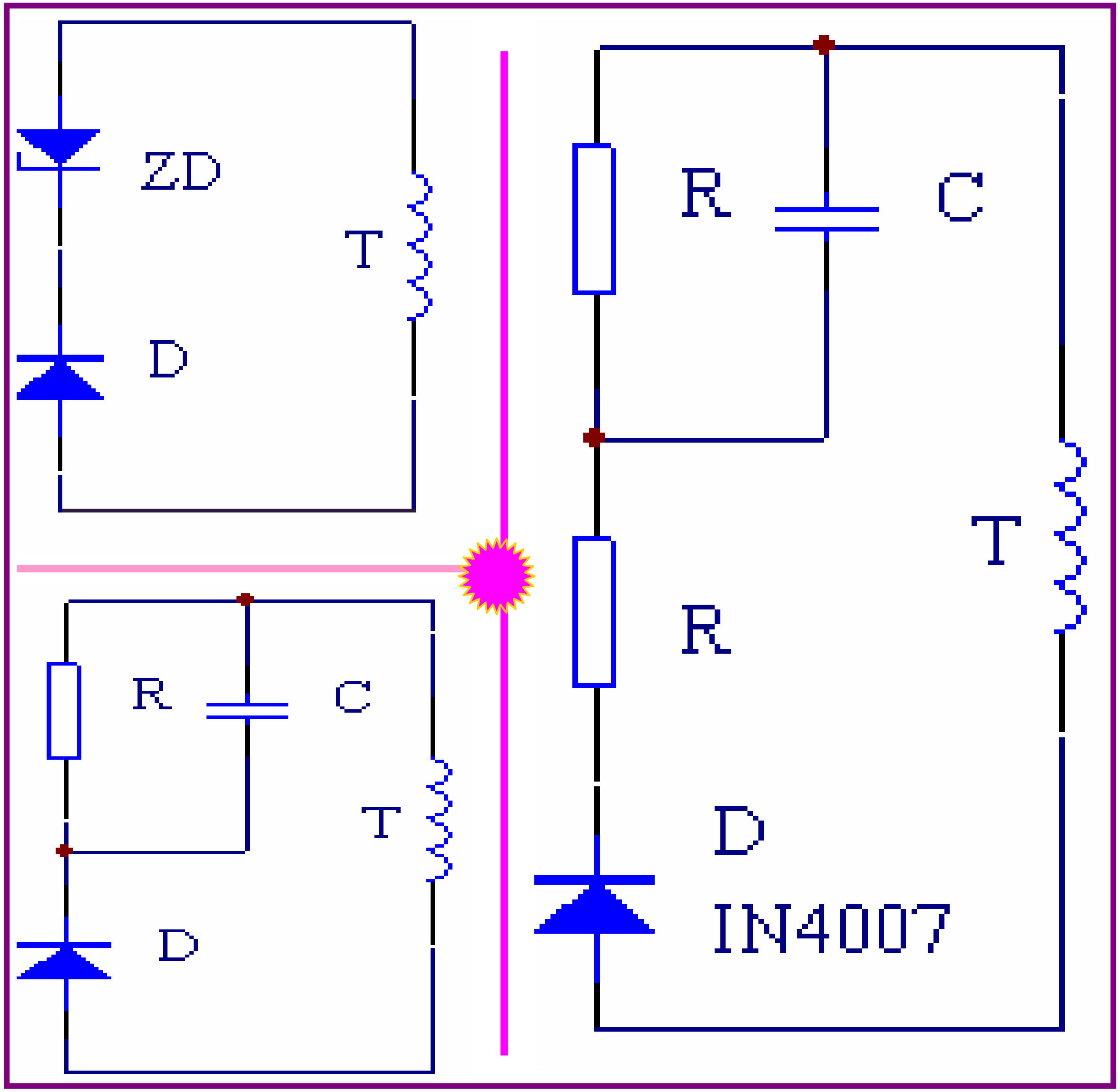
Design consideration

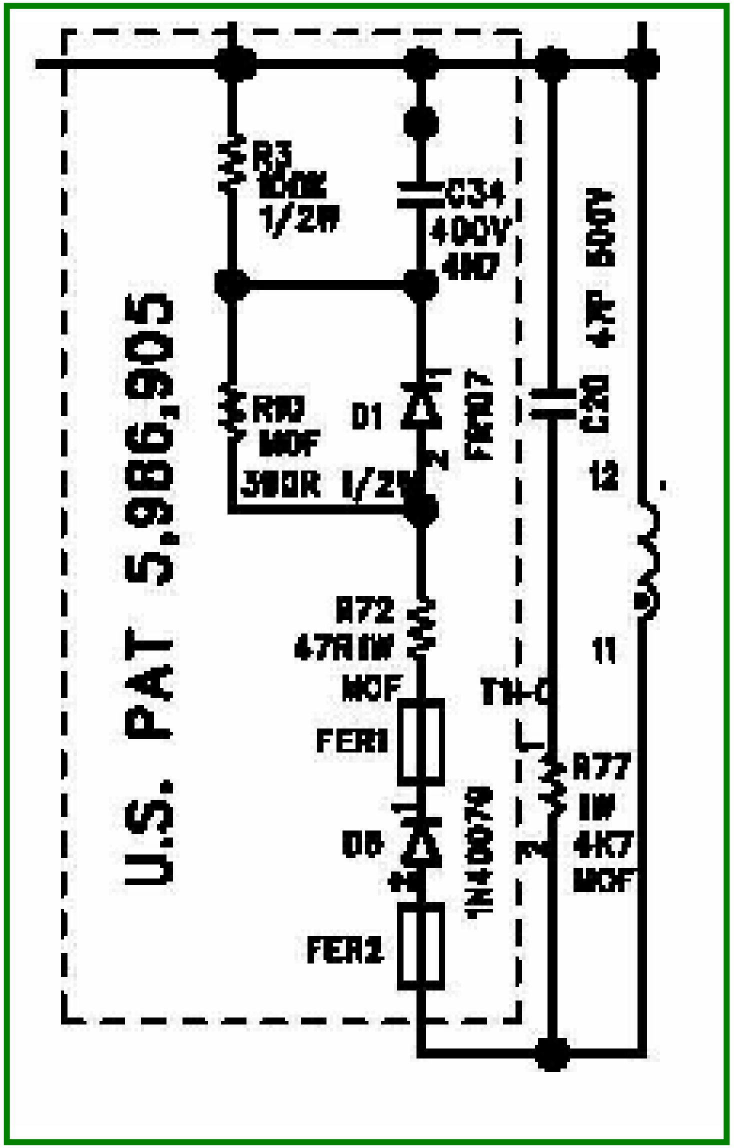
1 Effective leakage inductance and causes energy stored in leakage inductance
2 Short circuit current
3 Cross regulation
4 Diode voltage drops
5 Capacitor ripple voltage
6 Open loop fly back operation



Leakage is caused by the imperfect coupling between the primary and the secondary windings. It is not affected by changing the core material. Usually expressed as a percentage of winding inductance.

Fly Back


ZD
T
D
R
C
T
D
R
C
R
T
D
IN4007


U.S. PAT 5,986,905
R3
100K
1/2W
C34
400V
4N7
R10
MOF
390R 1/2W
D1
FR107
C30 4N7 500V
12
11
R72
47R 1W
MOF
FER1
D6
1N4007
FER2
TH-C
R77
1W
4K7
MOF

Fly Back

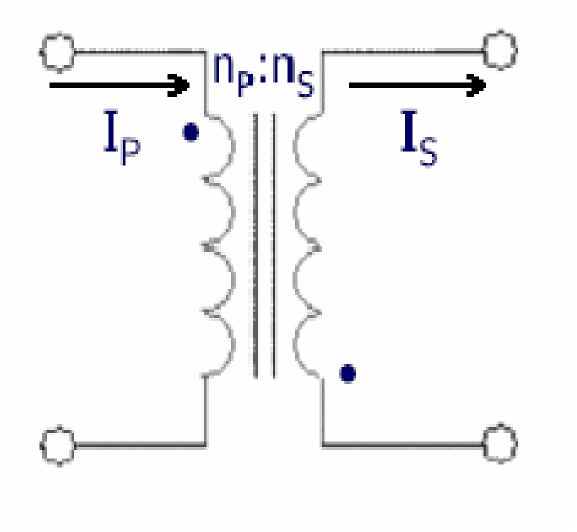
1 The fly back does not need a reset winding since the core is mad to de-saturate during turn off. The core is made to store all the input energy during turn on before it is allowed to deliver the energy to the load during turn off. a high power transformer is needed for the fly back than the forward converter.

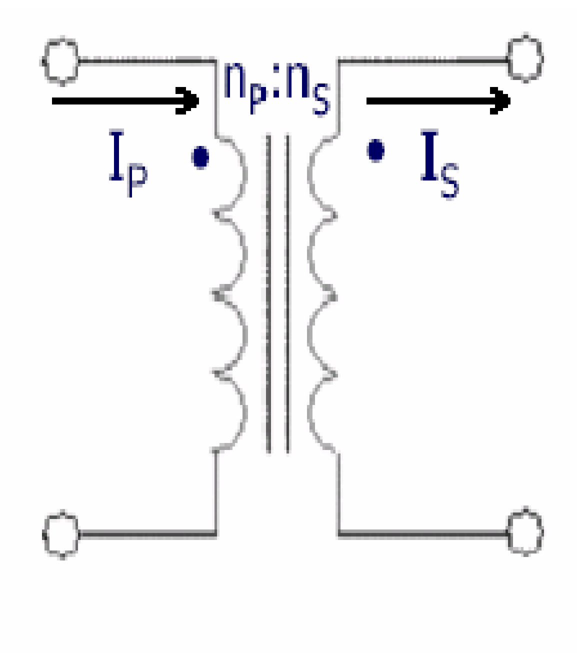
2 To be able to store significant amount of energy in the core, an air gap is required since considerably more energy can be stored in the air gap than in the ferromagnetic part of the core.

3 Only one output can be directly regulated with other outputs acting as slaves. Multi-regulation will affect the regulation rate.

4 Feedback loop is easily stabilized with DCM. Vo/Vin= D/n(1-D), the term (1-D) in the denominator constitutes a Right Half Plane Zero and has a dramatic effect on the response of the circuit to sudden load changes, reducing gain slope by 20dB/decade but increasing phase lag by 90. The only way to stabilize the feedback loop during CCM is to drastically reduce the error amplifier bandwidth for reducing response time.

Fly Back





Unlike a forward transformer, the secondary winding of a fly back transformer has a polarity that of the primary winding. A forward transformer is a voltage transformer in the practical sense. The fly back transformer is effectively a current transformer

Fly Back advantages and disadvantages over Forward converter

Advantages:

More than one output is possible on one supply
Output voltage range highly
Simple design
Only one output diode needed and inductance no needed
Voltage between primary and secondary is lower than for a forward

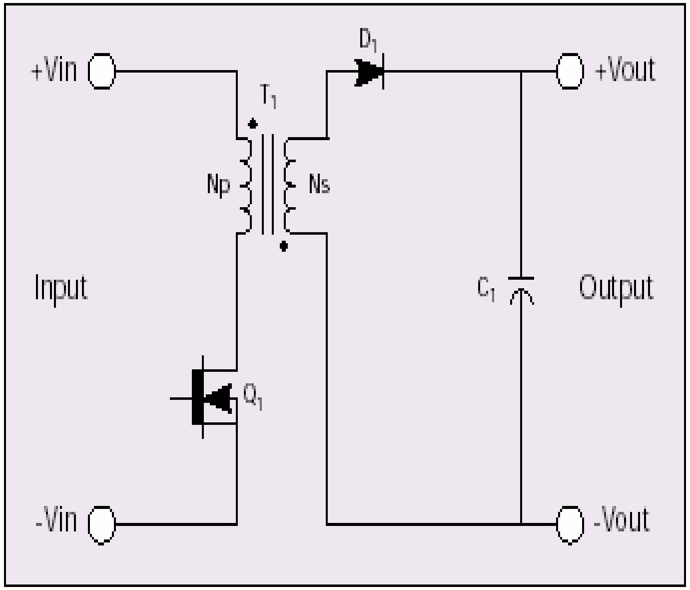
Disadvantages:

Generally less efficient
Leakage inductance energy needs to be dissipated in snubber, in forward the energy goes back to the source via the reset winding.

Fly Back

The fly back topology is one of the most common and cost-effective means of generating moderate levels of isolated power in AC/DC converters. Additional output voltages can be generated easily by adding additional secondary windings. There are some disadvantages. however. Regulation and output ripple are not as tightly controlled as in some of the other topologies and the stresses on the power switch are higher.

Useful power level: 5 to 150 Watts
Switch voltage stress: $V_{in} + (N_p/N_s)\ V_{out}$
Switch power stress: P_{in}
Transformer utilization: Poor/specialized design
Duty cycle: <0.5
Output ripple frequency: f_S
Relative cost: Low-moderate

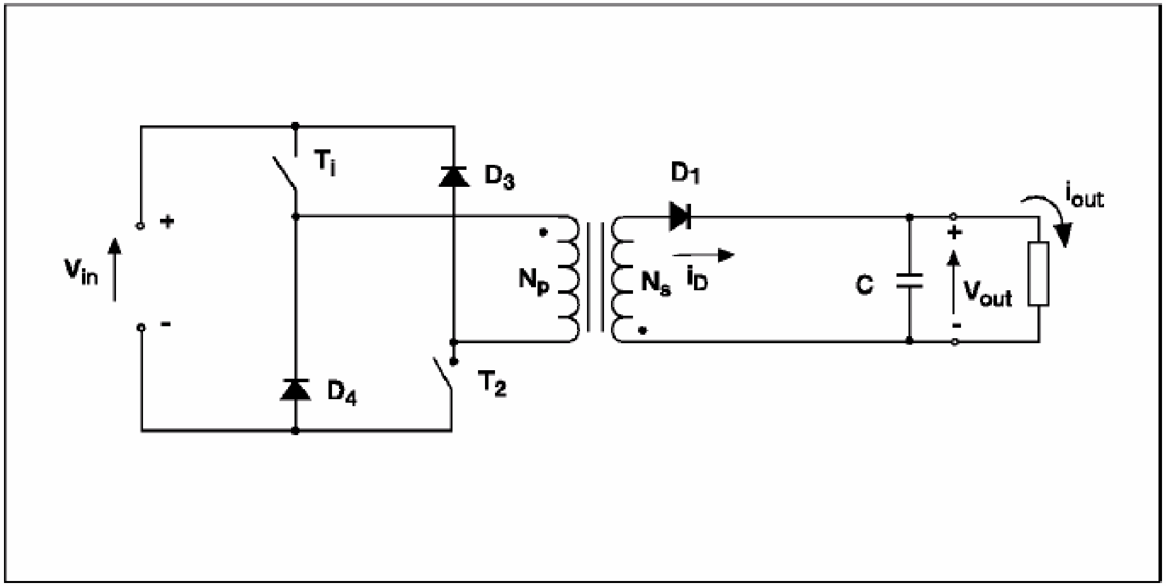


Fly Back

A double switch fly back converter

In the single switch fly back, an over voltage spike is applied across the power switch at each turn off. The peak value of this over voltage depends upon the switching time, the circuit capacitance and the primary to secondary transformer leakage inductance. So, a single switch fly back nearly always requires a snubber circuit limiting this voltage spike. In a double switch fly back, the leakage inductance of the power transformer is much less critical. The two demagnetization diodes D1 andD2 provide a single non dissipative way to systematically clamp the voltage across the switches to the input DC voltage Vin. This energy recovery system allows us to work at higher switching frequencies and with a better efficiency than that of the single switch structure. However, the double switch structure requires driving a high side switch. This double switch fly back is also known as asymmetrical half bridge fly back.

Fly Back



Power Switch: $V_{DDS} > V_{inmax}$

Primary Rectifier: $V_{RRM} > V_{inmax}$

Fly Back

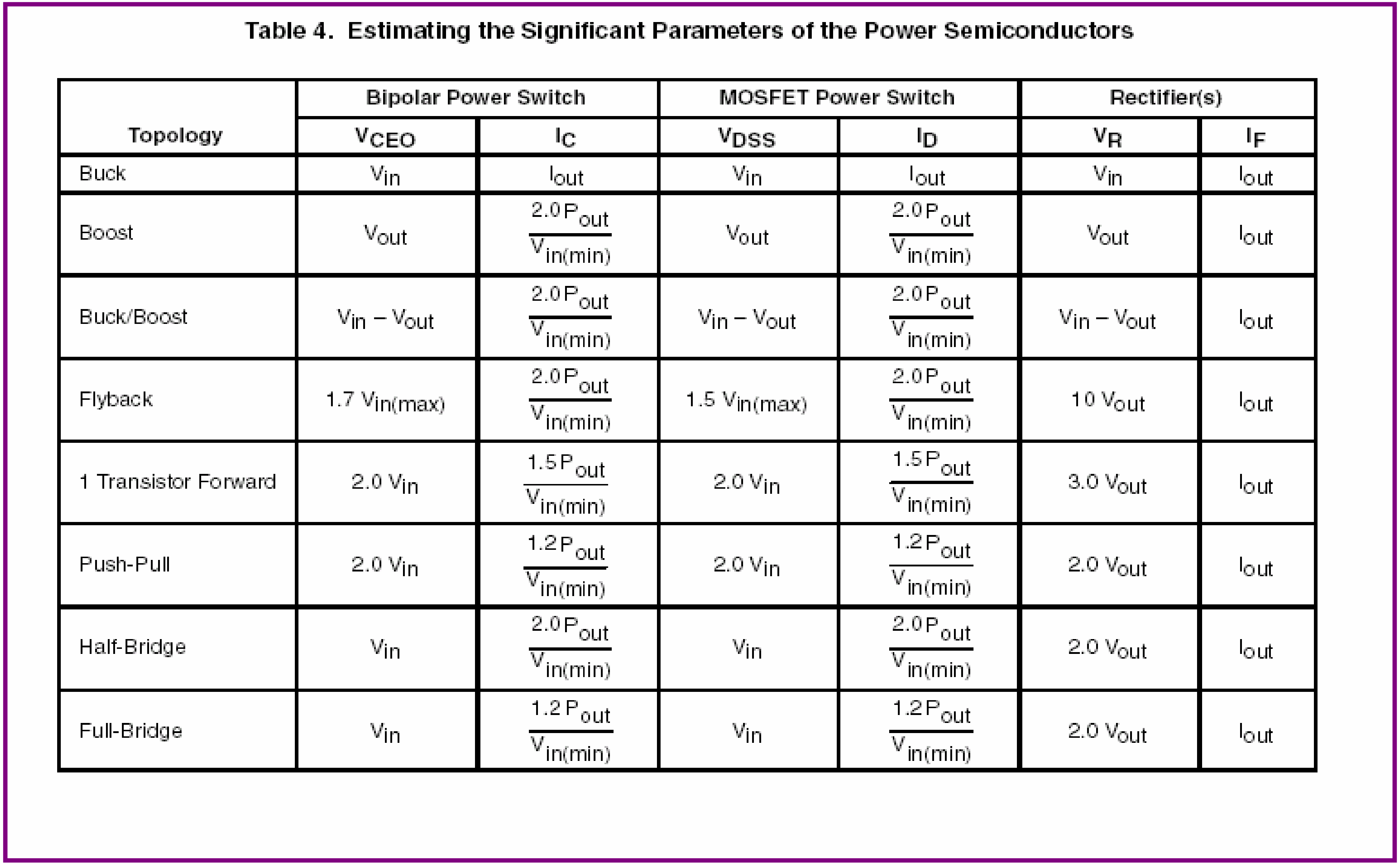


Table 4. Estimating the Significant Parameters of the Power Semiconductors

Topology	Bipolar Power Switch		MOSFET Power Switch		Rectifier(s)	
	V_{CEO}	I_C	V_{DSS}	I_D	V_R	I_F
Buck	V_{in}	I_{out}	V_{in}	I_{out}	V_{in}	I_{out}
Boost	V_{out}	$\frac{2.0 P_{out}}{V_{in(min)}}$	V_{out}	$\frac{2.0 P_{out}}{V_{in(min)}}$	V_{out}	I_{out}
Buck/Boost	$V_{in} - V_{out}$	$\frac{2.0 P_{out}}{V_{in(min)}}$	$V_{in} - V_{out}$	$\frac{2.0 P_{out}}{V_{in(min)}}$	$V_{in} - V_{out}$	I_{out}
Flyback	$1.7\ V_{in(max)}$	$\frac{2.0 P_{out}}{V_{in(min)}}$	$1.5\ V_{in(max)}$	$\frac{2.0 P_{out}}{V_{in(min)}}$	$10\ V_{out}$	I_{out}
1 Transistor Forward	$2.0\ V_{in}$	$\frac{1.5 P_{out}}{V_{in(min)}}$	$2.0\ V_{in}$	$\frac{1.5 P_{out}}{V_{in(min)}}$	$3.0\ V_{out}$	I_{out}
Push-Pull	$2.0\ V_{in}$	$\frac{1.2 P_{out}}{V_{in(min)}}$	$2.0\ V_{in}$	$\frac{1.2 P_{out}}{V_{in(min)}}$	$2.0\ V_{out}$	I_{out}
Half-Bridge	V_{in}	$\frac{2.0 P_{out}}{V_{in(min)}}$	V_{in}	$\frac{2.0 P_{out}}{V_{in(min)}}$	$2.0\ V_{out}$	I_{out}
Full-Bridge	V_{in}	$\frac{1.2 P_{out}}{V_{in(min)}}$	V_{in}	$\frac{1.2 P_{out}}{V_{in(min)}}$	$2.0\ V_{out}$	I_{out}