APPLICATION NOTE

# TOPOLOGIES FOR SWITCHED MODE POWER SUPPLIES

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## I INTRODUCTION

This paper presents an overview of the most important DC-DC converter topologies. The main object is to guide the designer in selecting the topology with its associated power semiconductor devices.

The DC-DC converter topologies can be divided in two major parts, depending on whether or not they have galvanic isolation between the input supply and the output circuitry.

## II NON - ISOLATED SWITCHING REGULATORS

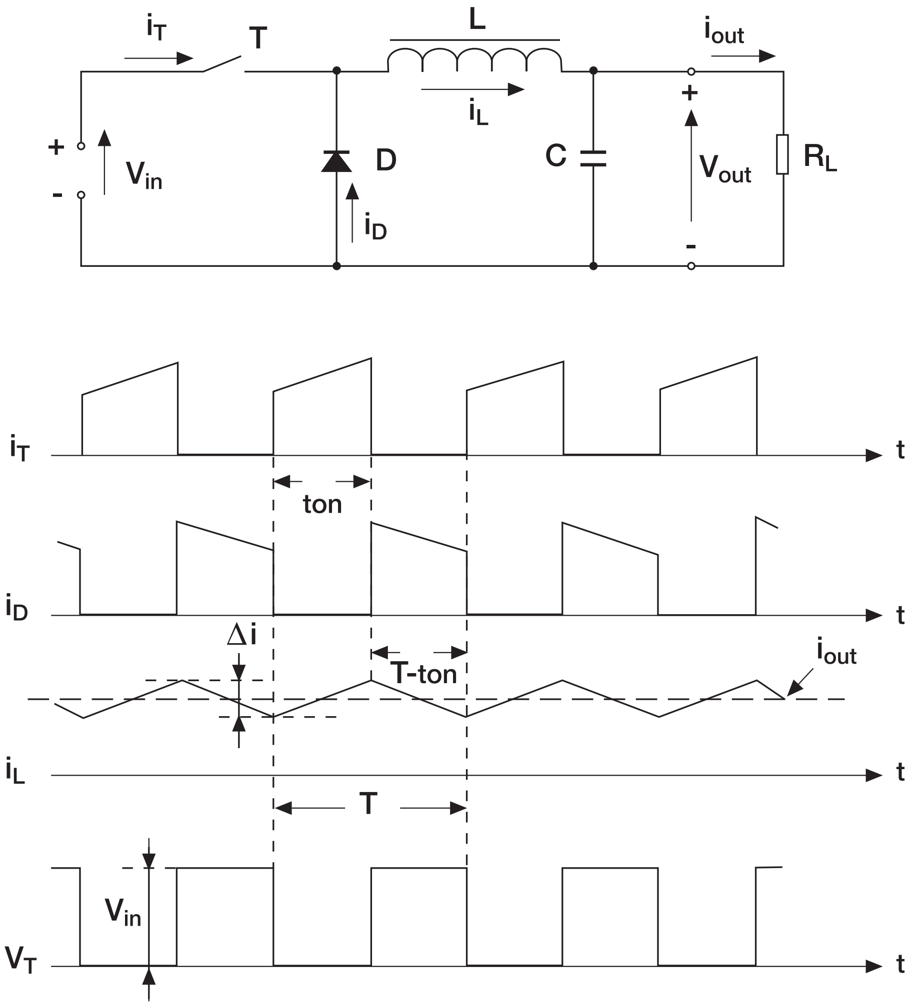
According to the position of the switch and the rectifier, different types of voltage converters can be made:

- Step down "Buck" regulator
- Step up "Boost" regulator
- Step up / Step down "Buck - Boost" regulator

### II - 1 The "Buck" converter: Step down voltage regulator

The circuit diagram, often referred to as a "chopper" circuit, and its principal waveforms are represented in figure 1:

**Figure 1:** The step down “Buck” regulator




The power device is switched at a frequency f = 1/T with a conduction duty cycle, $\delta = t_{on}/T$. The output voltage can also be expressed as: $V_{out} = V_{in} \cdot \delta$

Device selection:

** Power switch:* $V_{cev}$ or $V_{DSS} > V_{in\,max}$

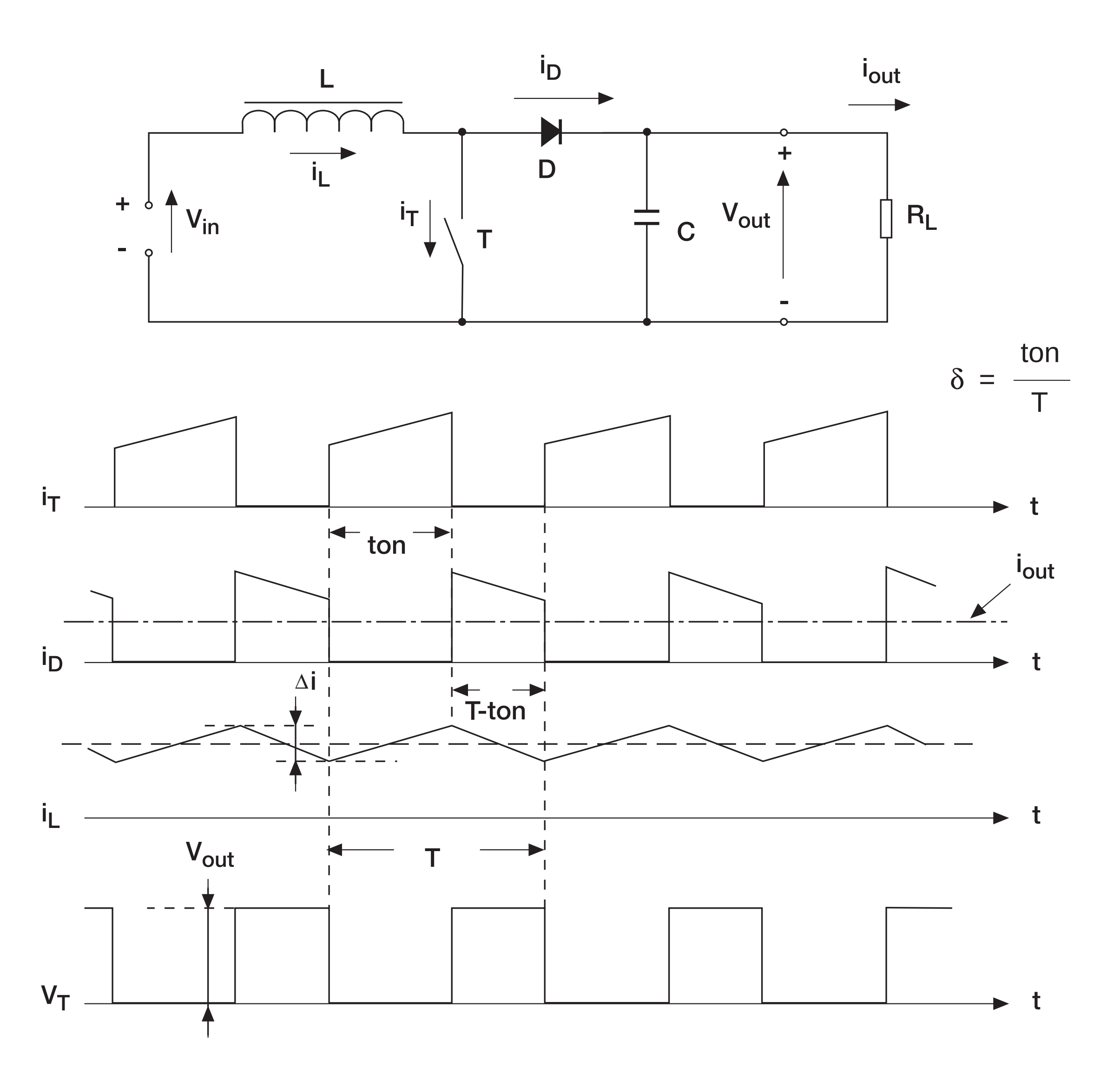
$$I_{cmax} \text{ or } I_{D\,max} > I_{out} + \frac{\Delta I}{2}$$

** Rectifier:* $V_{RRM} \geq V_{in\,max}$

$$I_{F(AV)} \geq I_{out}\,(1-\delta)$$

## II.2 The “Boost” converter: Step up voltage regulator

**Figure 2 :** The step up “Boost” regulator




In normal operation, the energy is fed from the inductor to the load, and then stored in the output capacitor. For this reason, the output capacitor is stressed a lot more than in the Buck converter.

$$V_{out} = \frac{V_{in}}{1-\delta}$$

Device selection:

** Power switch:* $V_{cev}$ or $V_{DSS} > V_{out}$

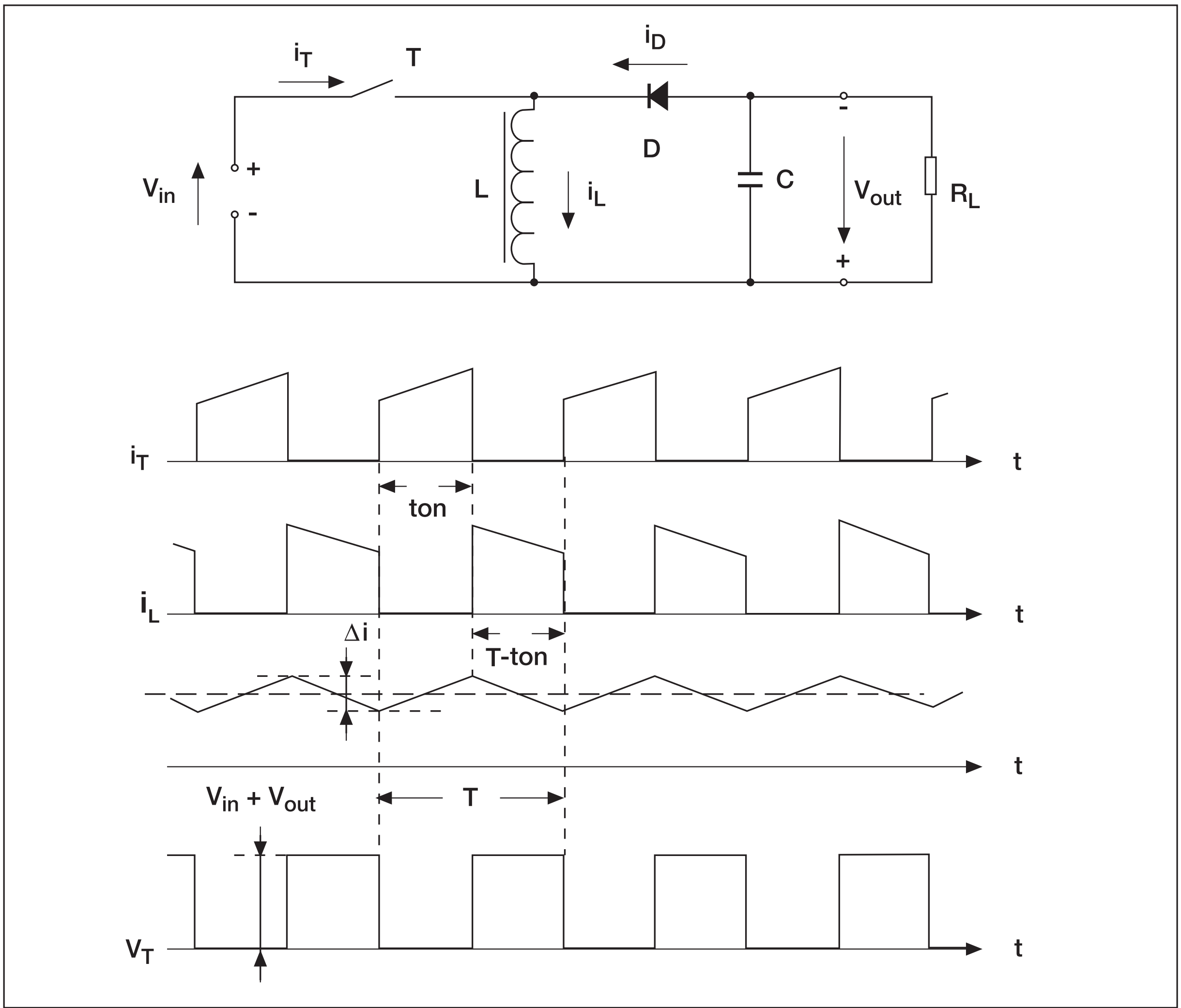
$$I_{cmax} \text{ or } I_{Dmax} > \frac{I_{out}}{1-\delta} + \frac{\Delta I}{2}$$

** Rectifier:* $V_{RRM} > V_{out}$

$I_{F(av)} > I_{out}$

## II - 3 "Buck-Boost converter: Step up/Step down voltage regulator

**Figure 3 :** The step up/step down "Buck-Boost" regulator




For a duty cycle under 0.5 the conversion works in step down mode, for a duty cycle over 0.5, the converter then operates in the step up mode.

$$V_{out} = -\frac{V_{in}.\delta}{1-\delta}$$

Device selection:

** Power switch* :

$$V_{cevmax} \text{ or } V_{DSS} > V_{inmax} + V_{out}$$

$$I_{cmax} \text{ or } I_{Dmax} > \frac{I_{out}}{1-\delta} + \frac{\Delta I}{2}$$

** Rectifier:*

$$V_{RRM} > V_{inmax} + V_{out}$$

$$I_{F\,(av)} > I_{out}$$

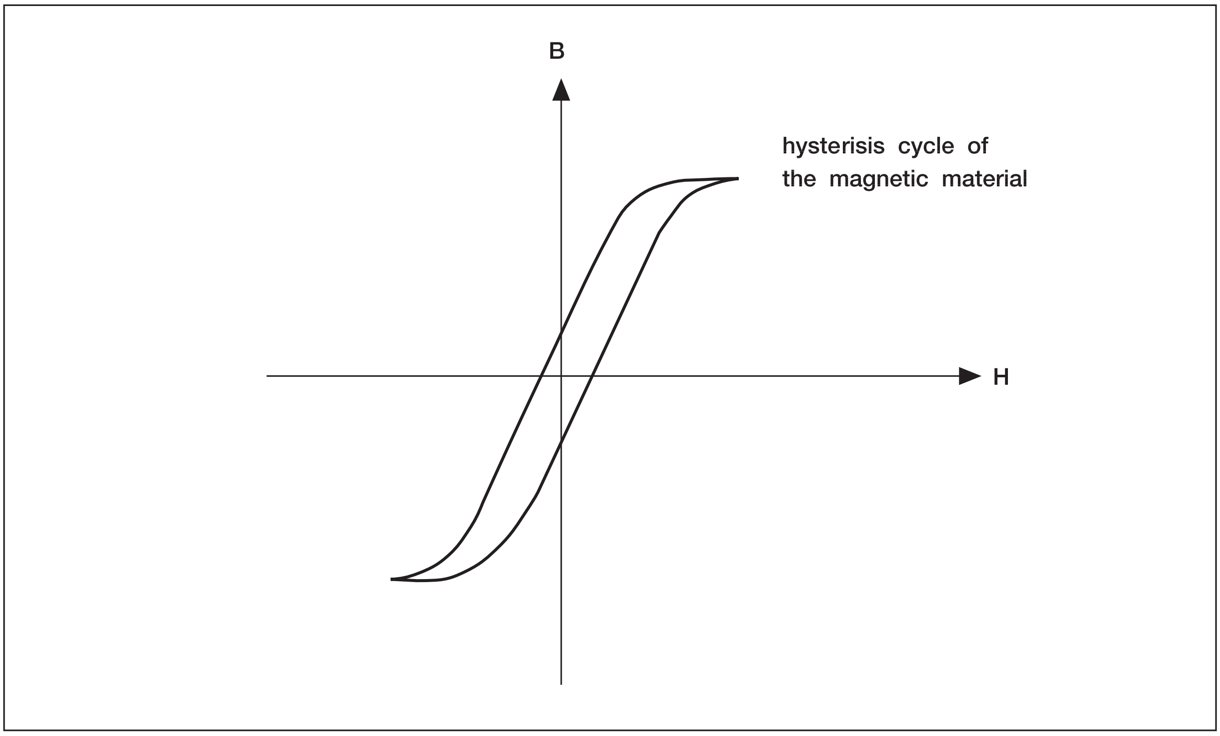
### II.4 Summery

| | 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 |

## III - ISOLATED CONVERTERS:

The isolated converters can be classified according to their magnetic cycle swing in the B-H plot (see figure 4). An isolated converter is asymmetrical if the magnetic operating point of the transformer remains in the same quadrant. Any other converter is, of course, called symmetrical.

**Figure 4 :** B-H plot of symmetrical converters



## III - 1 Asymmetrical converters

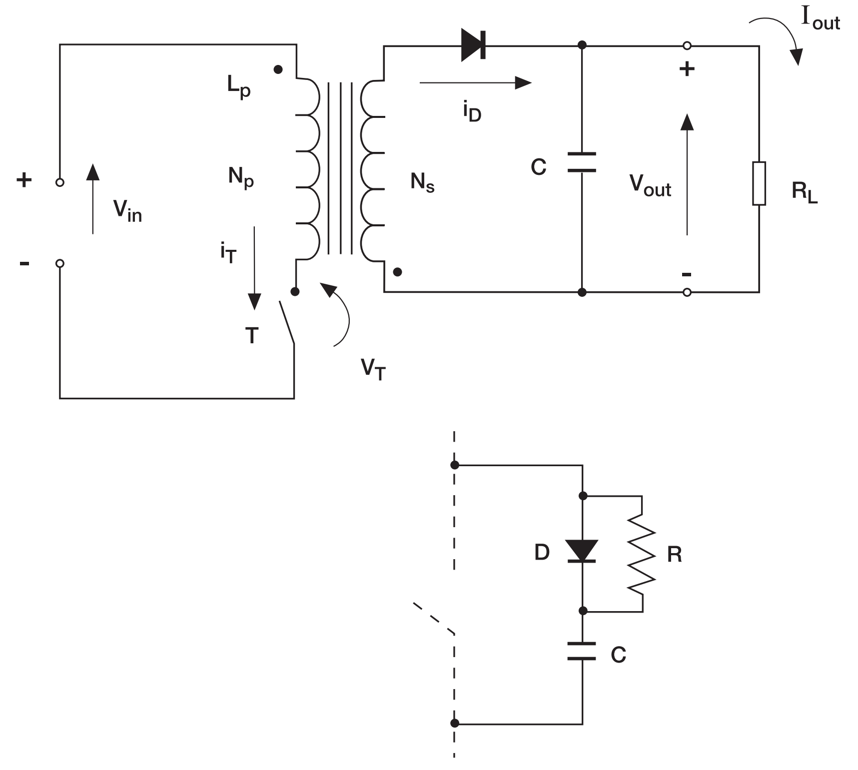
### III - 1.1 Off-line flyback regulators

The energy is stored in the primary $L_p$ inductance of the transformer during the time the power switch is on, and transferred to the secondary output when the power switch is off. If $n = N_p / N_s$ is the turns ratio of the transformer we have:

$$V_{out} = \frac{V_{in}}{n} \cdot \frac{\delta}{1-\delta}$$

Off-line flyback regulators are mainly used for an output power ranging from 30W up to 250W. Flyback topology is dedicated to multiple low cost output SMPS as there is no filter inductor on the output.

**Figure 5 :** Isolated single switch flyback




**Power switch:*

$$V_{CEV} \text{ or } V_{DSS} \geq V_{inmax} + nV_{out} + \text{leakage inductance spike}$$

** Secondary Rectifier:*

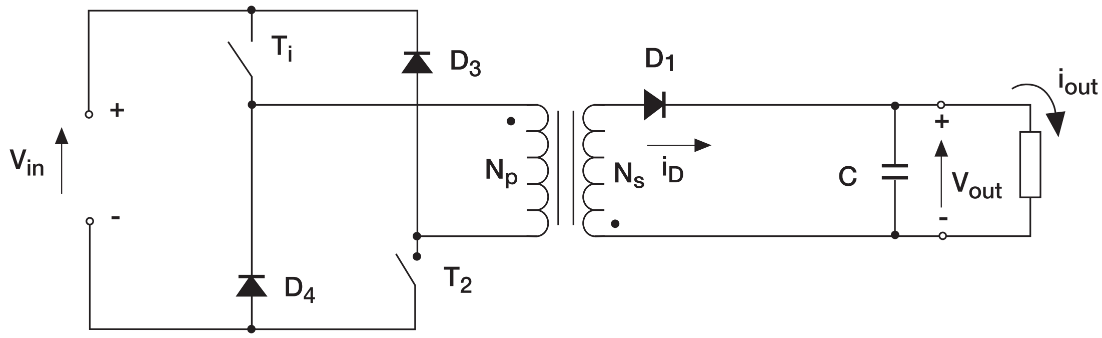
$$V_{RRM} \geq V_{out} + \frac{V_{inmax}}{n}$$

**a. Single switch versus double switch flyback**

In the single switch flyback, an overvoltage spike is applied across the power switch at each turn off. The peak value of this overvoltage depends upon the switching time, the circuit capacitance and the primary to secondary transformer leakage inductance. So, a single switch flyback nearly always requires a snubber circuit limiting this voltage spike (see figure 5).

In a double switch flyback, the leakage inductance of the power transformer is much less critical (see figure 6). The two demagnetization diodes ($D_1$ and $D_2$) provide a single non dissipative way to systematically clamp the voltage across the switches to the input DC voltage $V_{in}$. 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 flyback is also known as asymmetrical half bridge flyback.

**Figure 6:** Isolated double switch flyback




** Power switch:*

$$V_{CEV} \text{ or } V_{DSS} \geq V_{inmax}$$

** Primary Rectifiers: $D_3$ and $D_4$*

$$V_{RRM} \geq V_{inmax}$$

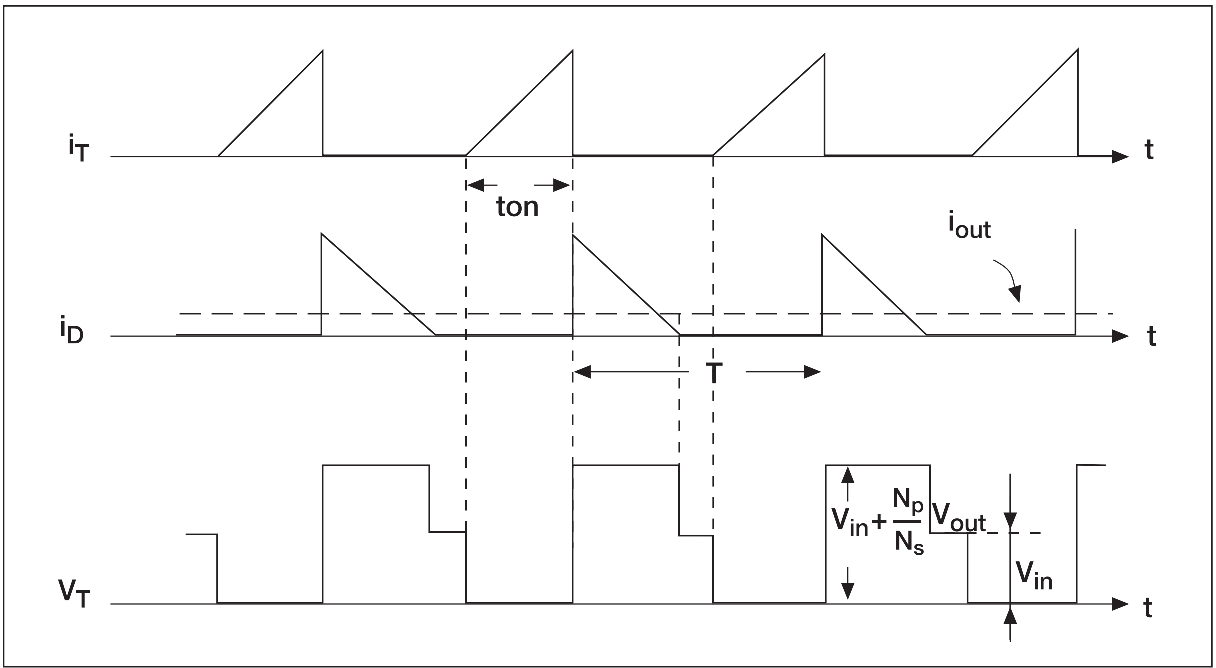
**b. Discontinuous versus continuous mode flyback**

The flyback converter has two operating modes depending whether the primary inductance of the transformer is completely demagnetized or not.

**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 | |

**Figure 7:** Discontinuous mode flyback waveforms



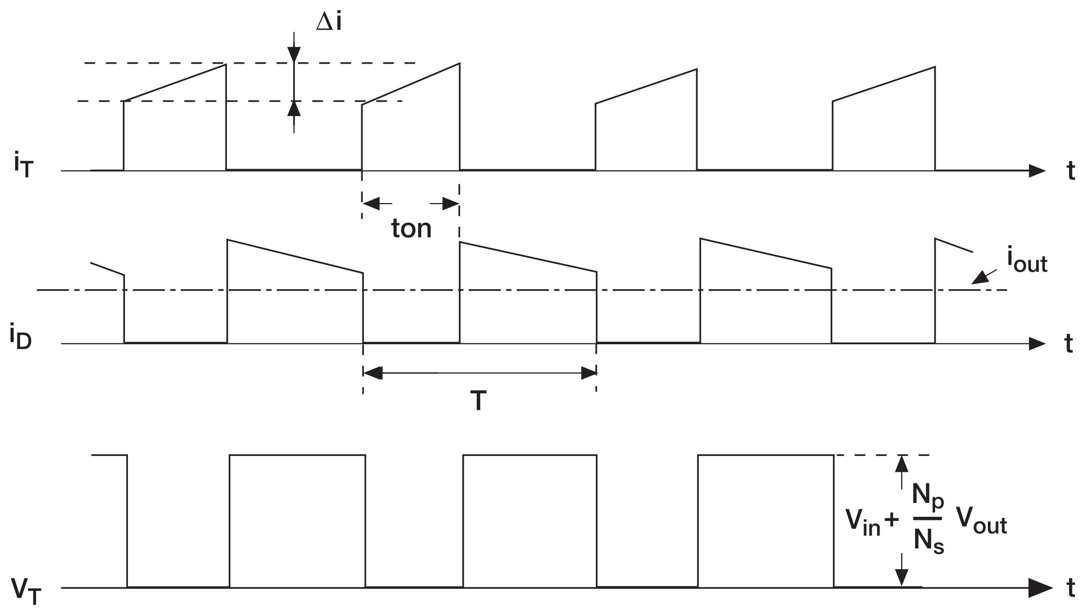

** Power switch:* $I_{Cpeak} \geq \dfrac{2P_{out}}{\eta V_{inmin}\ \delta_{max}}$  ** Rectifier:* $I_{Fpeak} \geq \dfrac{2P_{out}}{V_{out}\ (1-\delta_{max})}$

$$I_{Drms} \geq \frac{2P_{out}}{\eta V_{inmin}\sqrt{(3\delta_{max})}} \qquad I_{F(AV)} \geq \frac{P_{out}}{V_{out}}$$

## Continuous mode

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

**Figure 8:** Continuous mode flyback waveforms



** Power switch:*

$$I_{Cpeak} \geq \frac{2P_{outmax}}{\eta\ \delta_{max}\ V_{inmin}\ (1+A)}$$

$$I_{Drms} \geq \frac{2P_{out}}{\eta V_{inmin}} \sqrt{\left(\frac{(1 + A + A^2)}{3\delta_{max}}\right)}$$

** Rectifier:*

$$I_{Fpeak} \geq \frac{2P_{out}}{V_{out}\ (1 - \delta_{max})(1+A)}$$

$$I_F(AV) \geq \frac{P_{out}}{V_{out}}$$

$$\text{with } A \geq = \frac{I_{peak} - \Delta I}{I_{peak}}$$

### III - 1.2 Off line forward regulators

The forward converter transfers directly the energy from the input source to the load during the on-time of the power switch. During off-time of the power switch, the energy is freewheeling through the output inductor and the rectifier $D_2$, like in a chopper (see figure 1).

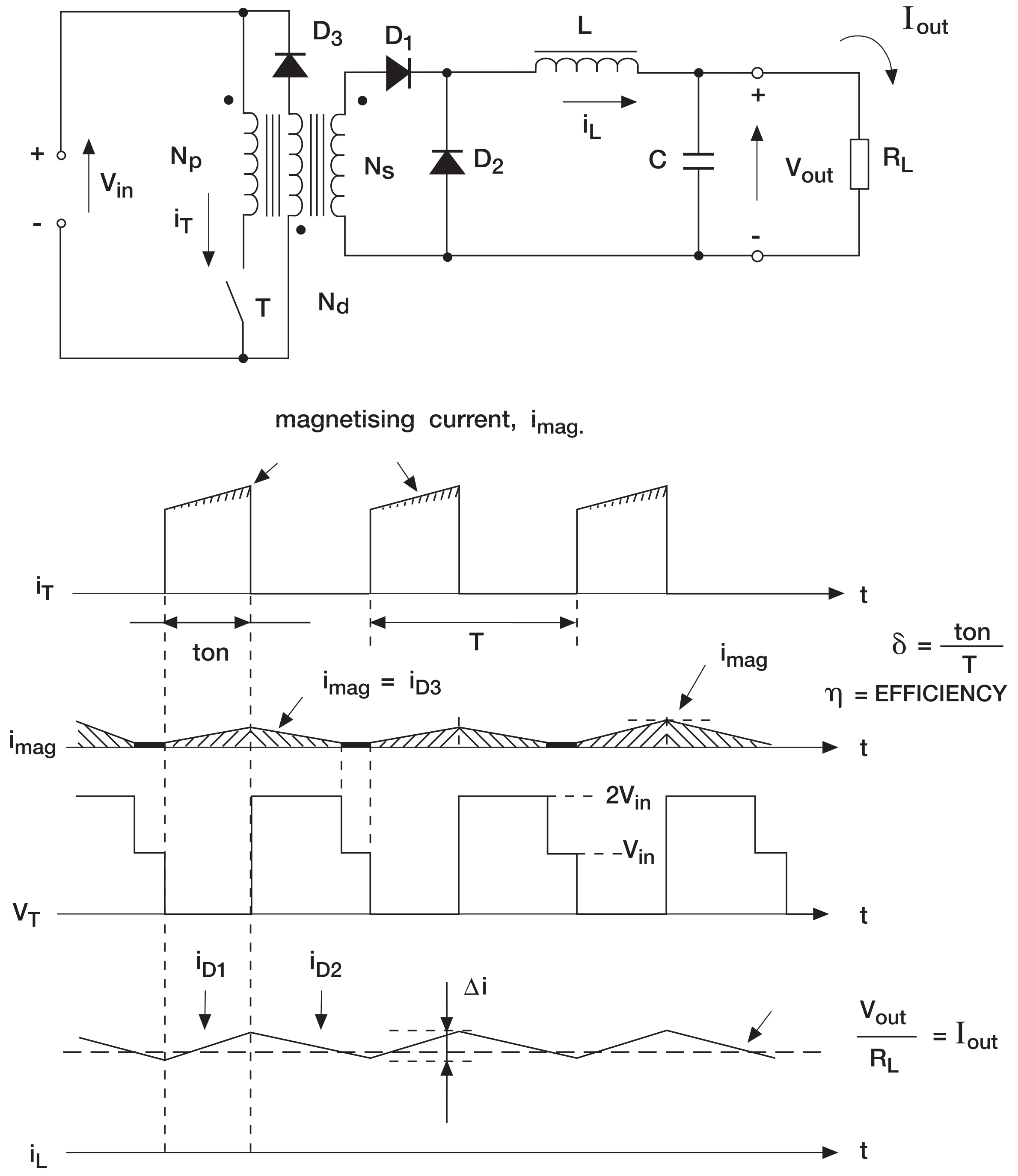
$$V_{out} = \delta \cdot \frac{V_{in}}{n}$$

A forward regulator can be realized with a single switch structure or with a double switch structure, according to the way the energy stored in the transformer primary inductance is demagnetized. Forward converters are commonly used for output power up to 250W in single switches, and up to 1kW in double switch structures.

**Single switch vs. double switch forward**

In the single switch forward, the magnetizing energy stored in the primary inductance is restored to the input source by a demagnetization winding $N_d$. Most commonly, the primary and the demagnetization windings have the same number of turns.
So, at turn-off, the power switch has to withstand twice the input voltage during the demagnetization time, and then, once the input voltage (see figure 9).
The demagnetization and primary windings have to be tightly coupled to reduce the voltage spike - more than the theoretical 2 $V_{in}$ - occuring at turn-off across the power switch.

**Figure 9:** Isolated single switch forward



** Power switch:*

$$V_{CEV} \text{ or } V_{DSS} \geq V_{inmax}\left[1 + \frac{N_p}{N_d}\right] + \text{leakage inductance spike}$$

$$I_{cpeak} \geq \frac{1.2.P_{out}}{\eta V_{inmin} \cdot \delta_{max}}$$

$$I_{Drms} \geq \frac{1.2.P_{out}}{\eta V_{inmin} \cdot \sqrt{\delta_{max}}}$$

**Rectifiers:*

FORWARD D1:

$$V_{RRM} \geq V_{inmax} \cdot \frac{N_s}{N_d} + \text{leakage inductance spike}$$

$$I_{F(av)} \geq I_{out} \cdot \delta_{max}$$

FREEWHEELING D2:

$$V_{RRM} \geq \frac{V_{inmax} \cdot (V_{out} + V_F)}{V_{inmin} \cdot \delta_{max}}$$

$$I_{F(av)} \geq I_{out}$$

DEMAGNETIZATION D3:

$$V_{RRM} \geq \left[1 + \frac{N_d}{N_p}\right] V_{inmax}$$

$$I_{F(av)} \geq \frac{I_{magnpeak}}{2} \cdot \delta_{max}$$

In the "double switch forward", also called asymmetrical half bridge forward, the magnetizing energy stored in the primary inductance is automatically returned to the bulk capacitor by the two demagnetization diodes $D_1$ and $D_2$.

The two power switches and demagnetisation diodes have to withstand only once the input voltage $V_{in}$. As for the double switch flyback, the asymmetrical half bridge needs a floating gate drive for the high side switch.

** Power switch:*

$$V_{CEV} \text{ or } V_{DSS} \geq V_{inmax}$$

$$I_{Drms} \geq \frac{1.2.P_{out}}{\eta V_{inmin} \cdot \sqrt{\delta_{max}}}$$

** Rectifiers:*

FORWARD D1:

$$V_{RRM} \geq \frac{V_{inmax}\ (V_{out} + V_F)}{V_{inmin}\ .\ \delta_{max}}$$

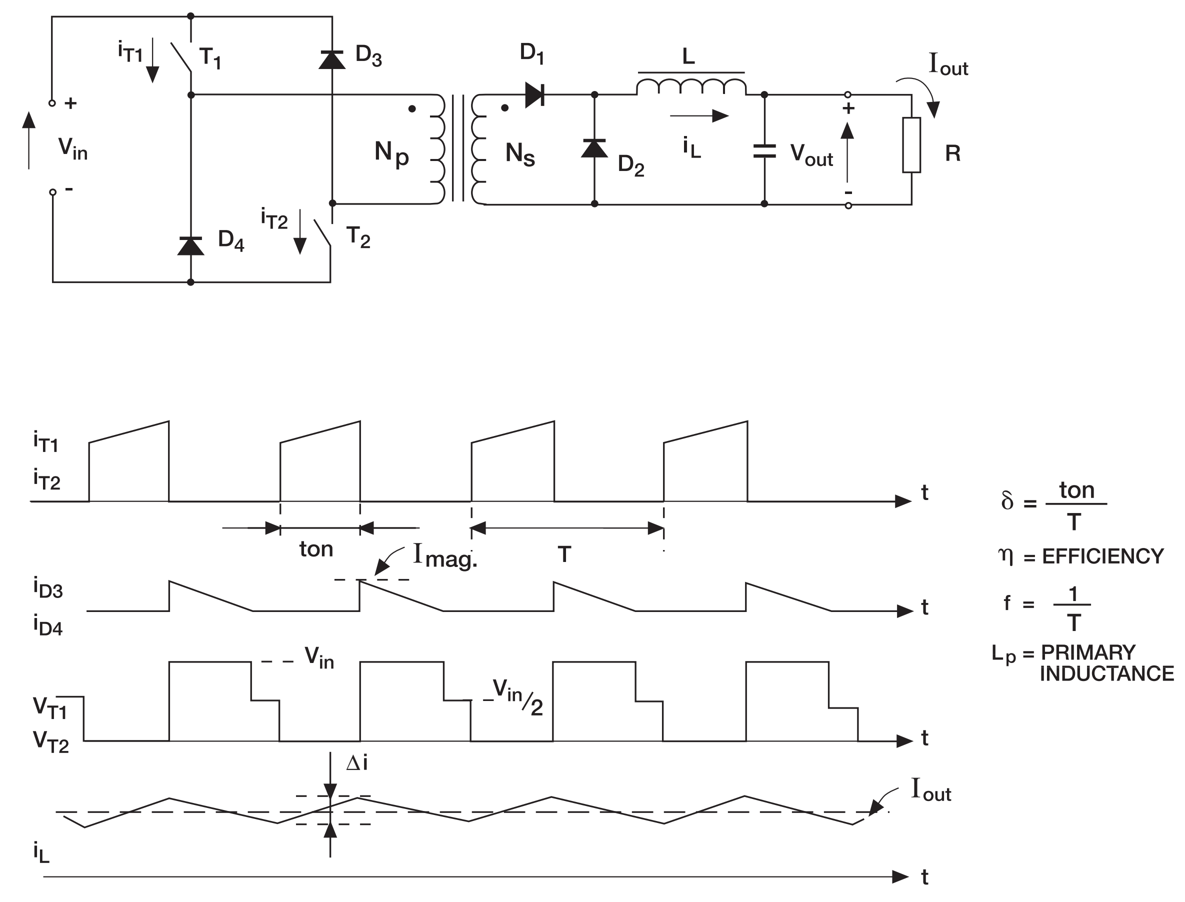
$$I_{F(av)} \geq I_{out}\ .\delta_{max}$$

FREEWHEELING D2:

$$V_{RRM} \geq V_{inmax}\ (V_{out} + V_F)$$

$$I_{F(av)} \geq I_{out}$$

**Figure 10:** Half bridge asymmetrical forward converter



### III - 2 Symmetrical converters

This type of converter always uses an even number of switches. It also better exploits the transformer's magnetic circuit than in asymmetrical converters. So, smaller size and weight can be achieved.

The three most common structures used are:

- PUSH/PULL
- HALF BRIDGE with capacitors
- FULL BRIDGE

### III - 2.1 Push/Pull converter

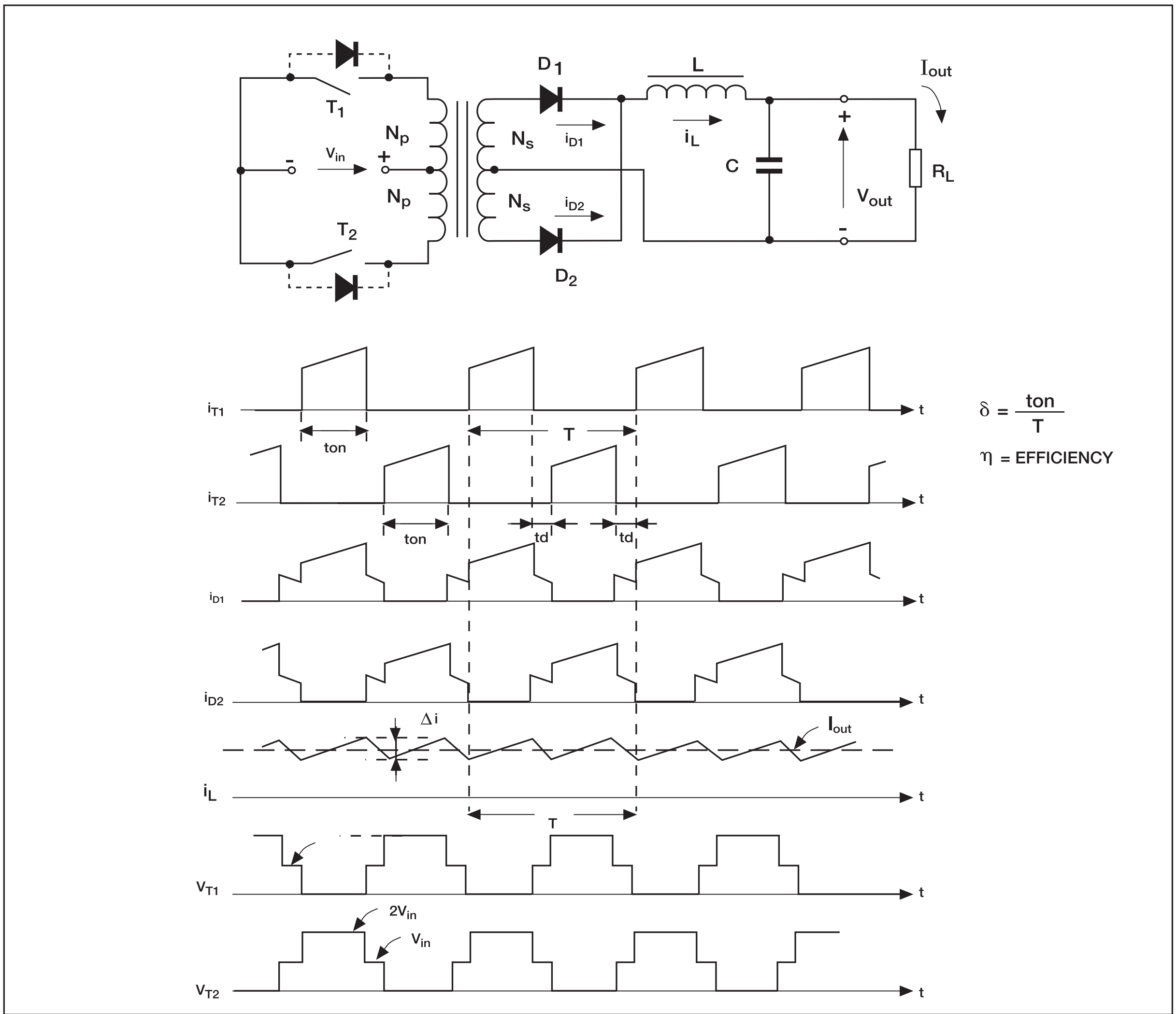
$T_1$ and $T_2$ switches (see figure 11) are alternately turned-on during a time $t_{on}$. The secondary circuit operates at twice the switching frequency.

A deadtime $t_d$ between the end of conduction of one switch and the turn-on time of the other one is required in order to avoid simultaneous conduction of the two switches.

$$V_{out} = 2\,\frac{\delta V_{in}}{n}$$

Moreover, the snubber network in symmetrical converters must be carefully designed, since they inter-react with one another.

**Figure 11:** Push-Pull converter



** Power switch*

$$I_{Dpeak} \text{ or } I_{Cpeak} \geq \frac{P_{out}}{\eta V_{inmin}}$$

$$V_{CEV} \text{ or } V_{DSS} \geq 2V_{inmax} + \text{leakage inductance spike}$$

** Rectifier*

$$V_{RRM} \geq \frac{(V_{out} + V_F)\, V_{inmax}}{\delta_{max} . V_{inmin}} + \text{Voltage spike}$$

$$I_{F(av)} \geq \frac{I_{outmax}}{2}$$

The switches are easy to drive since they are both referenced to ground, however they must withstand twice the input supply voltage.

The inherent flux symmetry problems can be corrected with a current mode PWM control circuit.

### III - 2.2 Half bridge converter

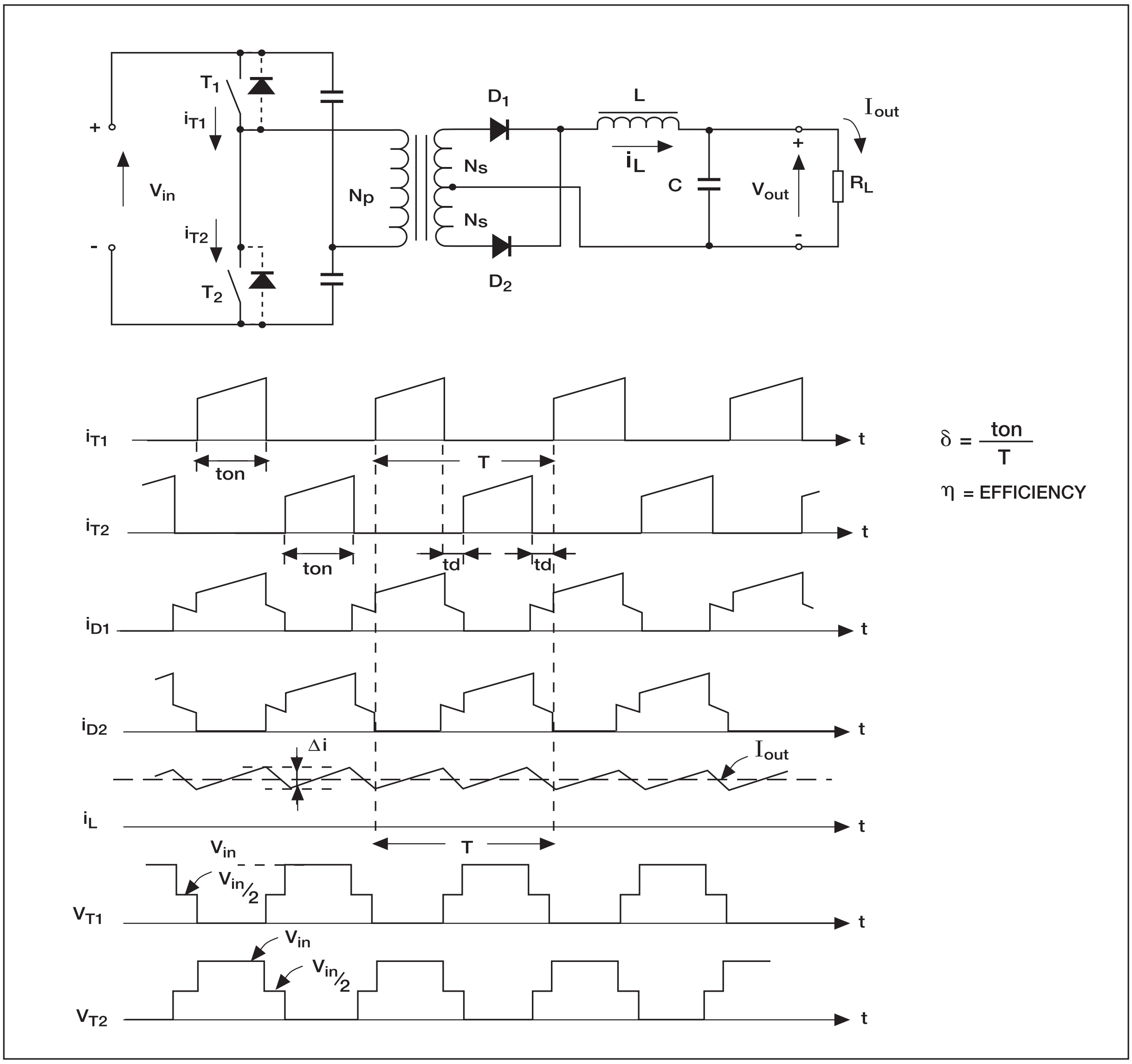
This topology can be used for an output power capability up to 500W. As for the push-pull converter, $T_1$ and $T_2$ switches are alternately turned on during a time $t_{on}$.

$$V_{out} = \frac{V_{in} . \delta}{n}$$

The capacitors in series across the supply fix a mid-point so that switches withstand only once the input voltage $V_{in}$.

However, this topology requires driving a high side switch. When using bipolar switches, transistor’s storage time should have tight tolerances to avoid imbalance in operating flux level.

**Figure 12:** Half bridge converter




** Power switch:*

$$I_{Cpeak} \text{ or } I_{Dpeak} \geq \frac{2P_{out}}{\eta V_{inmin}}$$

$$V_{CEV} \text{ or } V_{DSS} \geq V_{inmax}$$

** Rectifier:*

$$V_{RRM} \geq \frac{(V_{out} + V_F) \cdot V_{inmax}}{\delta_{max} \cdot V_{inmin}} + \text{leakage inductance spike}$$

$$I_{F(av)} \geq \frac{I_{outmax}}{2}$$

Deadtimes ($t_d$ an figure 12) between two consecutive switch conduction are absolutely mandatory to avoid bridge-leg short circuit.

### III - 2.3 Full bridge converter

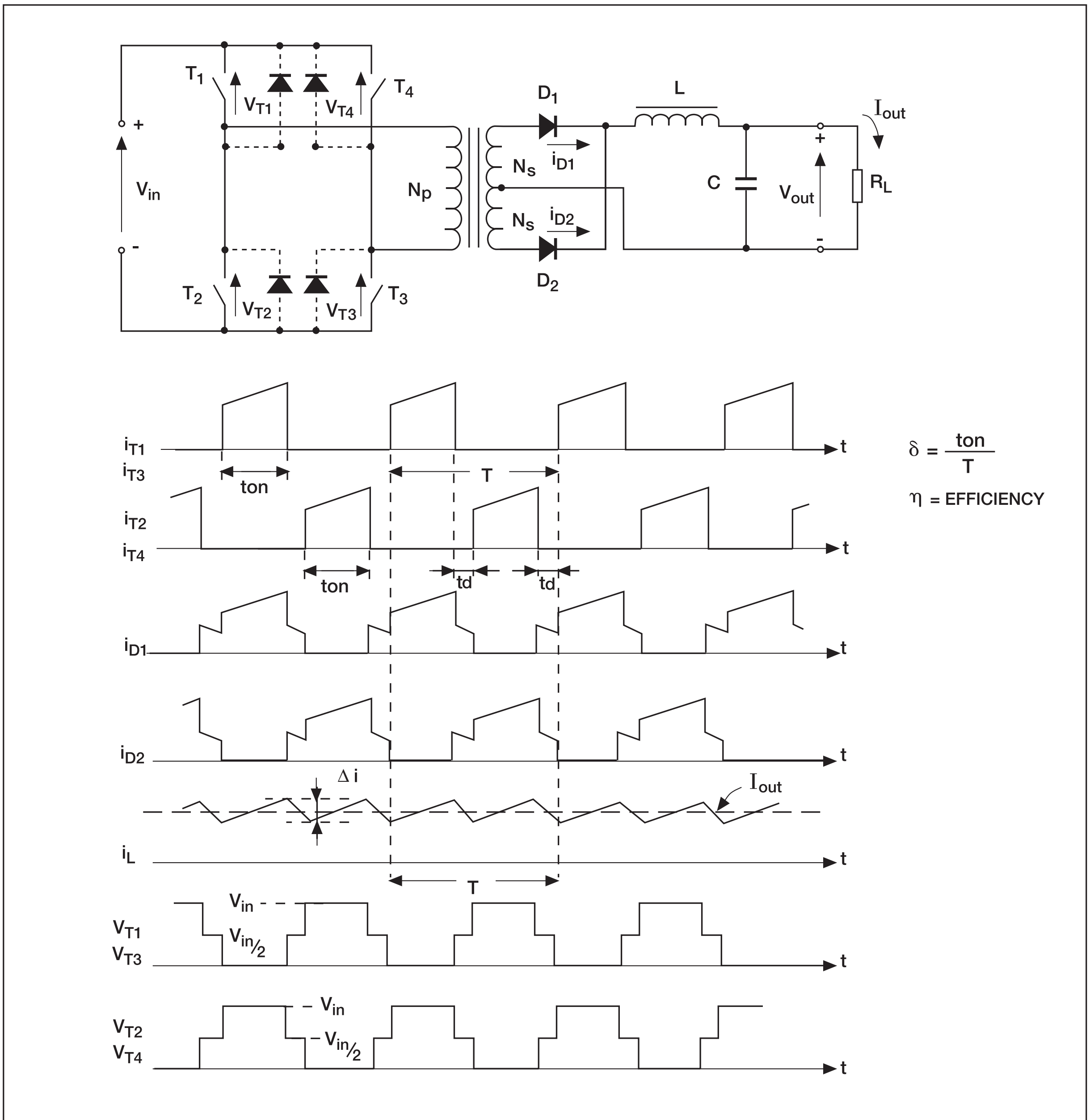
Because of the number of components, the full bridge is for high power applications, ranging from 500 up to 2000W.

Sometimes, power transformers are paralleled to provide higher output power.

$$V_{out} = \frac{2V_{in}\delta}{n}$$

Switch pairs $T_1$ and $T_3$, $T_2$ and $T_4$ are alternately driven.

**Figure 13:** Full bridge converter



** Power switch:*

$$I_{Cpeak} \text{ or } I_{Dpeak} \geq \frac{P_{out}}{\eta V_{inmin}}$$

$$V_{CEV} \text{ or } V_{DSS} \geq V_{inmax}$$

** Rectifier:*

$$V_{RRM} \geq \frac{(V_{out} + V_F)\ V_{inmax}}{\delta_{max}.V_{inmin}} + \text{leakage inductance spike}$$

$$I_F(av) \geq \frac{I_{outmax}}{2}$$

The full bridge provides twice the output power of the half bridge circuit with the same switch ratings.
Nevertheless, this topology requires 4 switches and clamping diodes.

## IV - CONCLUSION

Many significant technological changes in power supply design have resulted in lower cost per Watt with improved performance.

Today, designers keep going ahead with the state-of-the-art in switching regulator technology in order to reduce size and weight of power packages.

Output voltage and load current always depend upon the application. The power supply designs are often tailored to specific applications. No simple procedure exists to select the right topology.

This paper provides an overview of the most commonly used topologies and lists the most important features for each topology.