High Step-up Ratio DC-DC Converter Topologies

Part I

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Seminar Outline

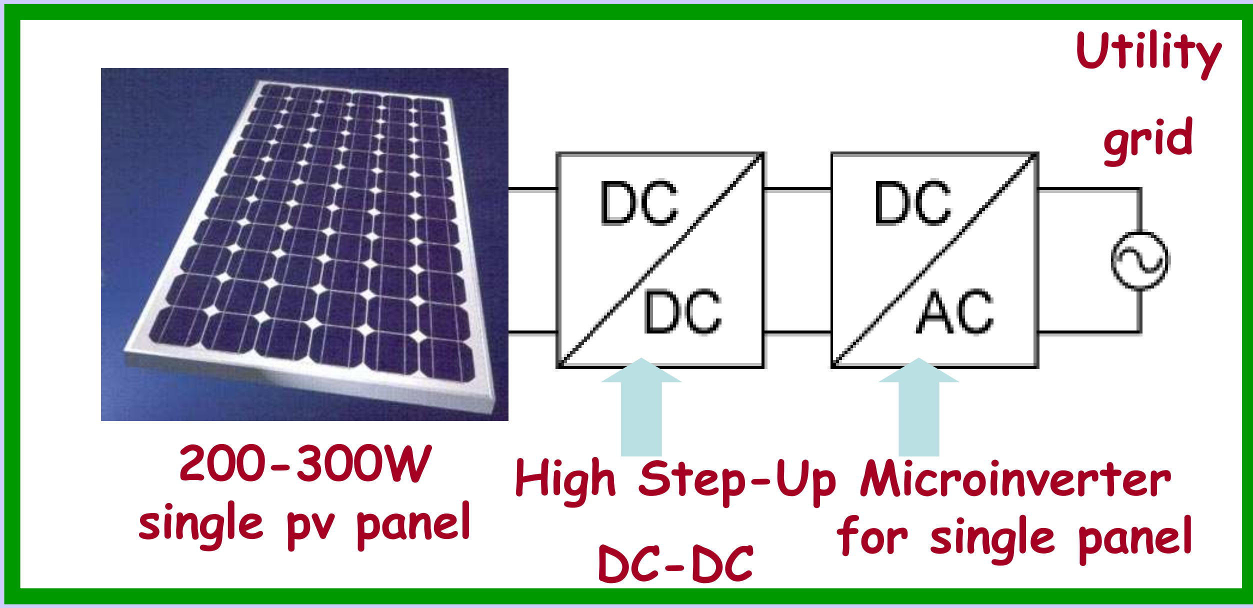
- Why we need high step-up ratio converters?
  - Application fields
- Low power high step-up ratio topologies
  - Coupled inductors
- High power high step-up ratio topologies
  - Non isolated
  - Isolated

High Step-up Ratio Topologies

Why?

- Low-voltage high-current energy sources
  - Fuel-cells (some kW)
  - Paralleled photovoltaic modules in domestic applications (some kW)
  - Microinverter, i.e. connection of a single photovoltaic module to the grid (some hundred watts)
- Step-down inverters require an input voltage higher than the maximum line voltage peak

Example of Microinverter

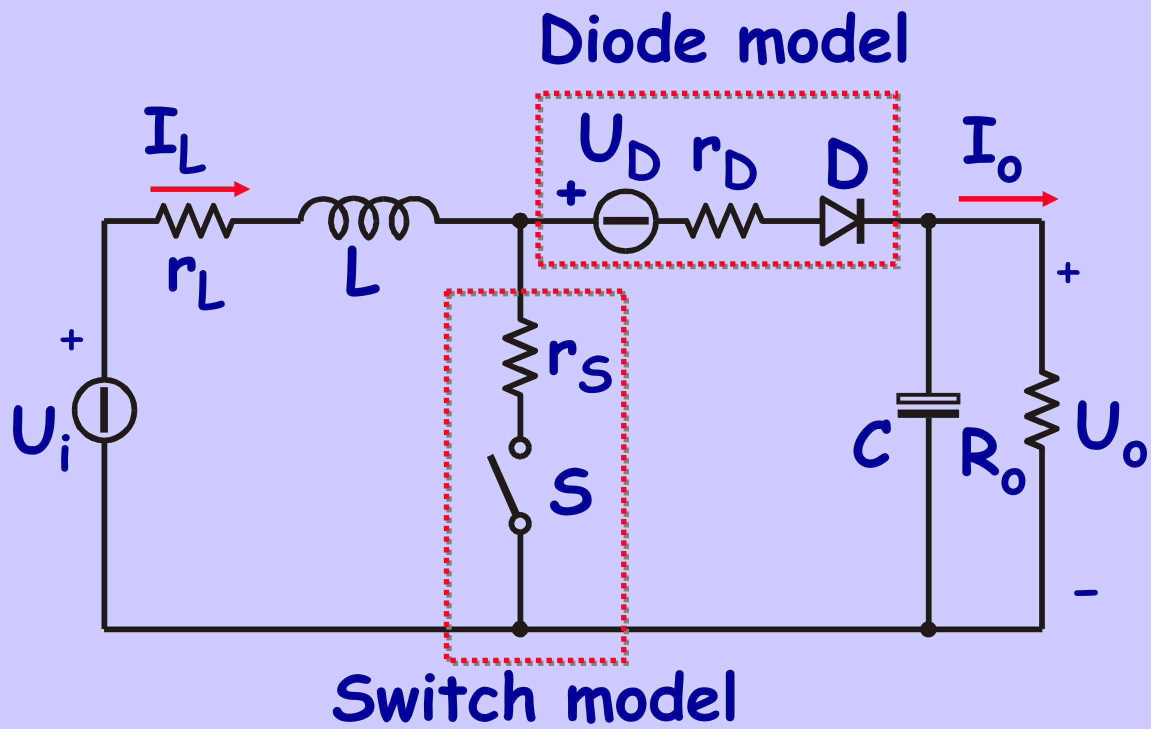


Microinverter structure

- Modularity
- Reduction of partial shading effects
- Dedicated Maximum Power Point Tracker (MPPT)

Simple Boost Topology

Boost scheme including some parasitic elements:

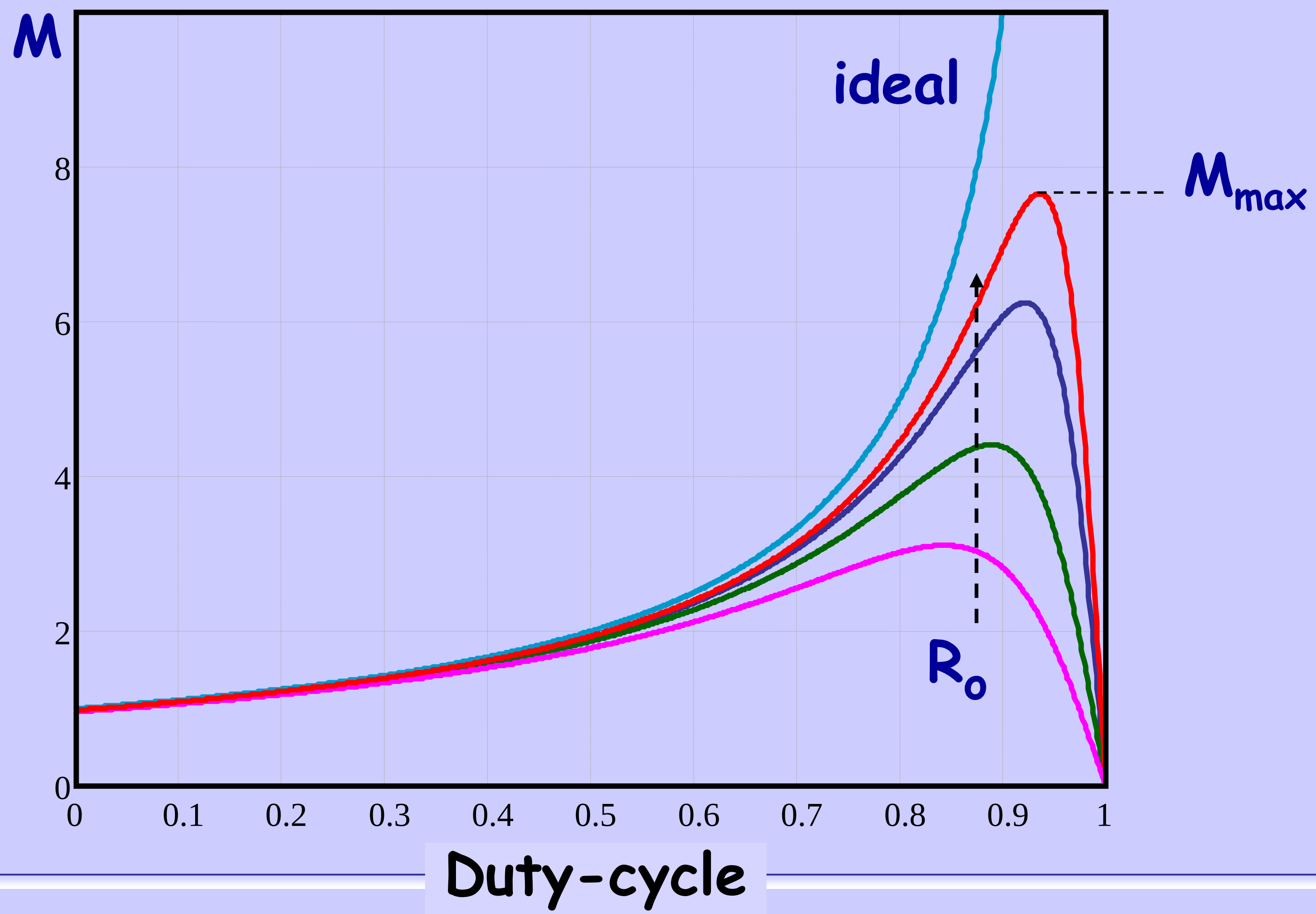


Voltage conversion ratio (neglecting inductor current ripple):

$$M = \frac{1}{1-d}\frac{1}{1+\frac{r_D(1-d)+r_S d+r_L}{R_o(1-d)^2}+\frac{U_D}{U_o}} = \frac{1}{1-d}\cdot F(d,U_o,R_o)$$

Simple Boost Topology

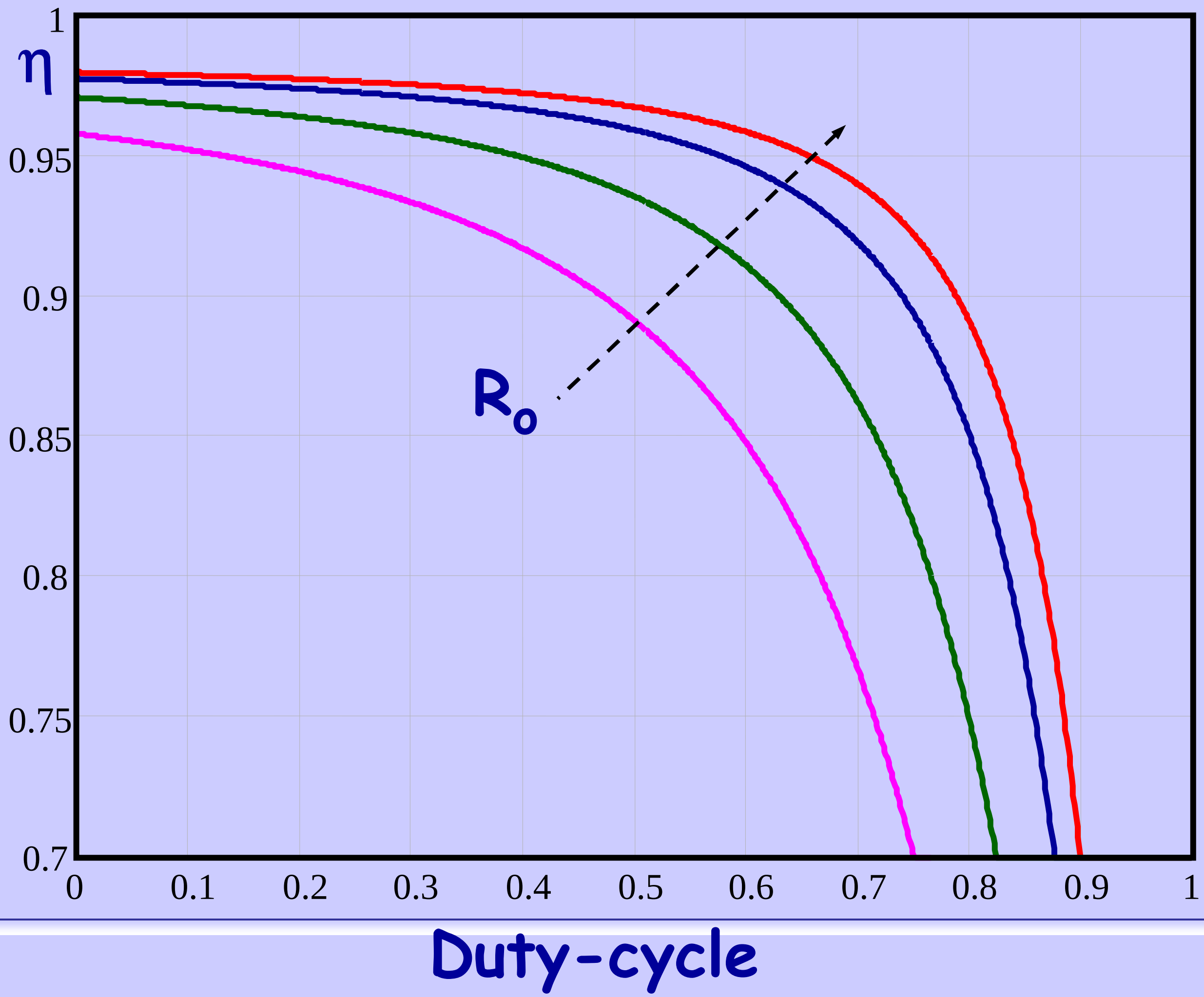
Voltage conversion ratio M including conduction losses:



Simple Boost Topology

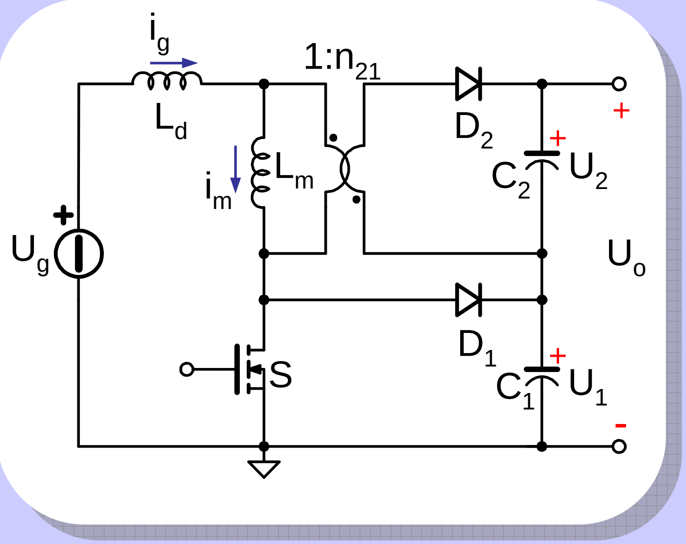
Converter efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{U_o I_o}{U_i I_i} = \frac{U_o I_D}{U_i I_L} = M(1-d) = F(d, U_o, R_o)$$



Low Power Applications

- **Example**: integrated Boost-Flyback converter

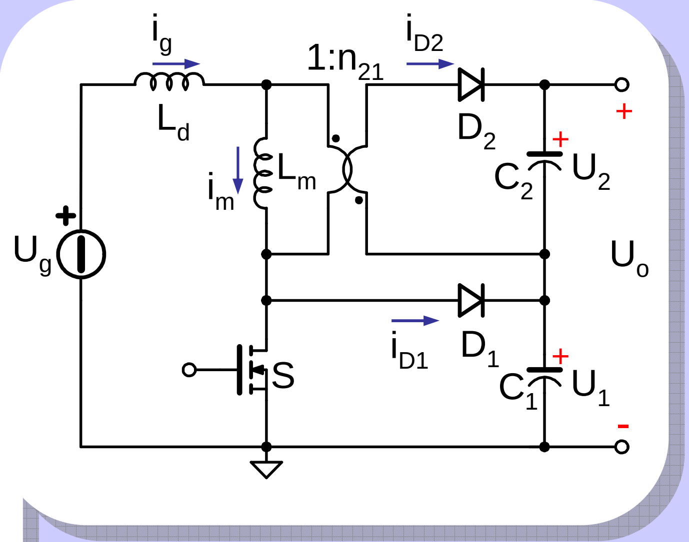


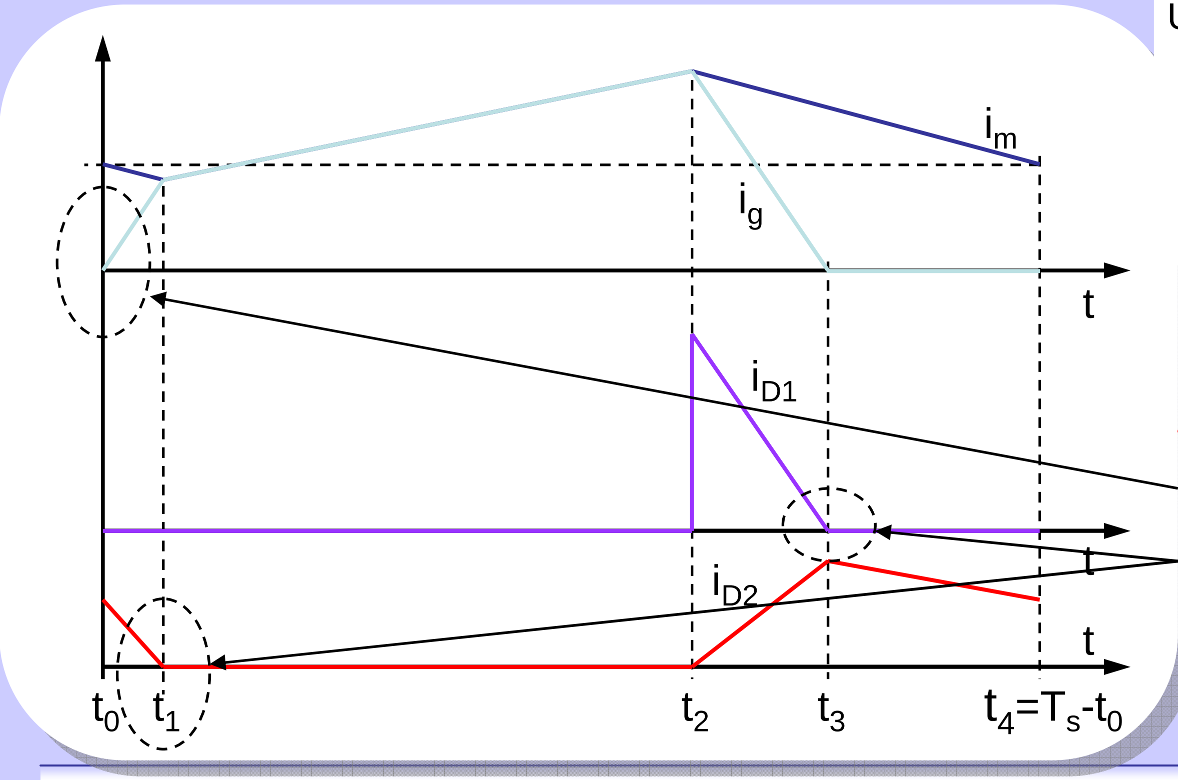
It can be seen as a flyback converter with a non dissipative snubber: D_1 and C_1 deliver to the output the energy stored in the transformer leakage inductance L_d

Integrated Boost-Flyback Converter

Ideal waveforms:

- CCM operation of flyback section
- DCM operation of boost section





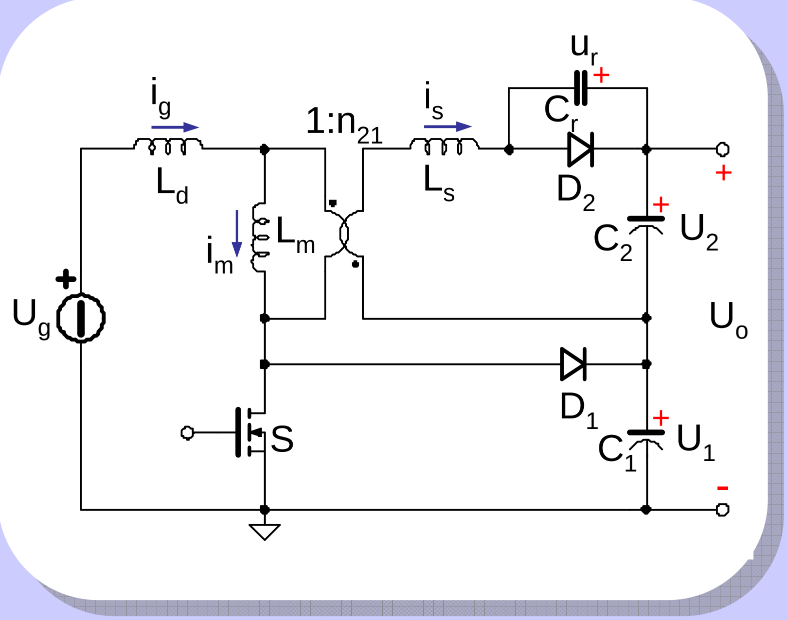
Advantages:

- ZCS turn on
- Soft diode turn off
- Reduced switch voltage stress

Integrated Boost-Flyback Converter

Problems:

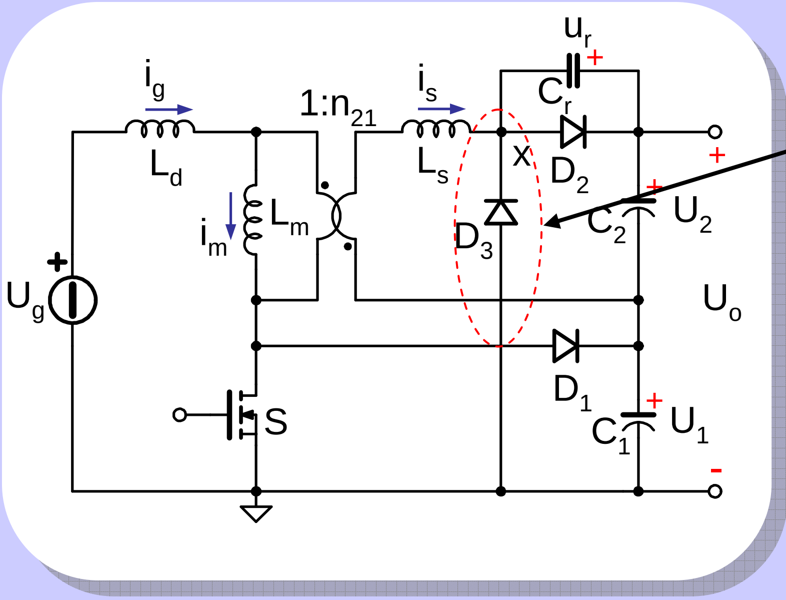
Parasitic oscillations at D_2 turn off caused by its capacitance C_r resonating with transformer leakage inductances L_d and L_s



High voltage stress across D_2

Dissipative R-C-D snubber is needed

Modified IBF Converter

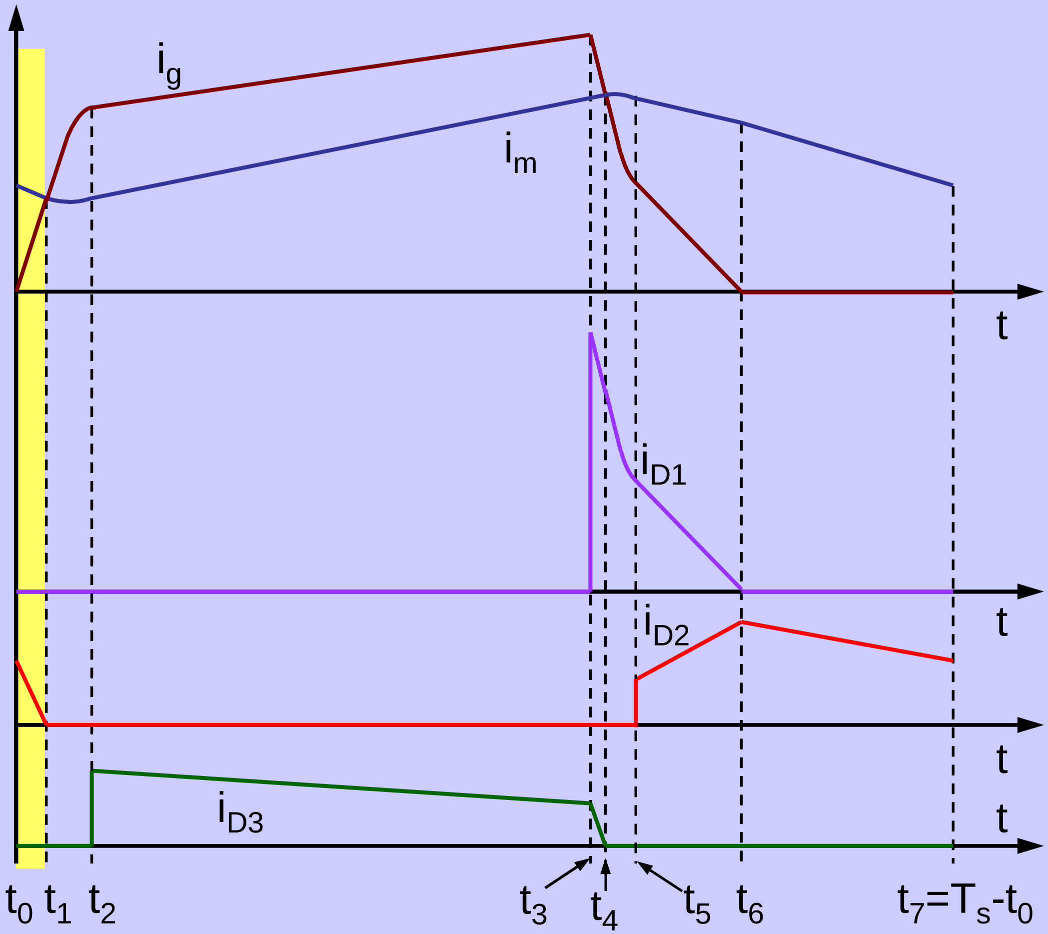


Clamping diode D_3 added to the original topology

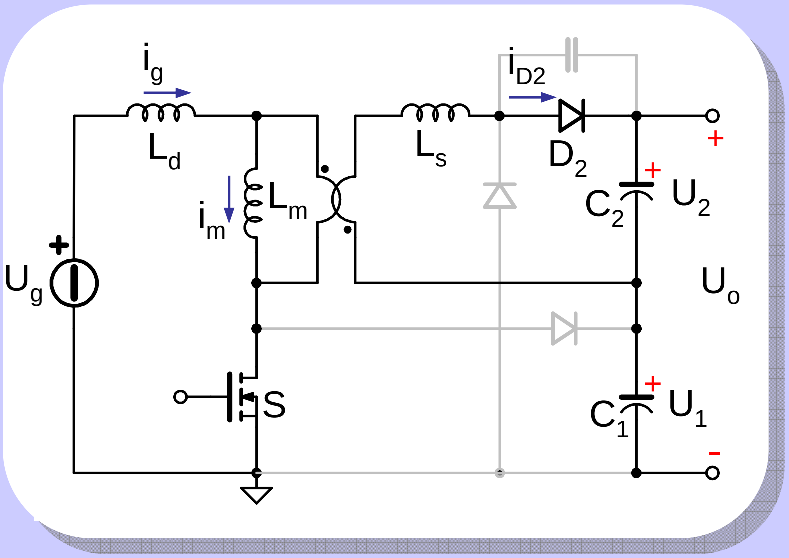
Advantages:

- Clean diode voltage waveforms without parasitic oscillations
- Energy transfer toward the output also during switch turn on interval
- Slight voltage gain increase due to resonances between parasitic components

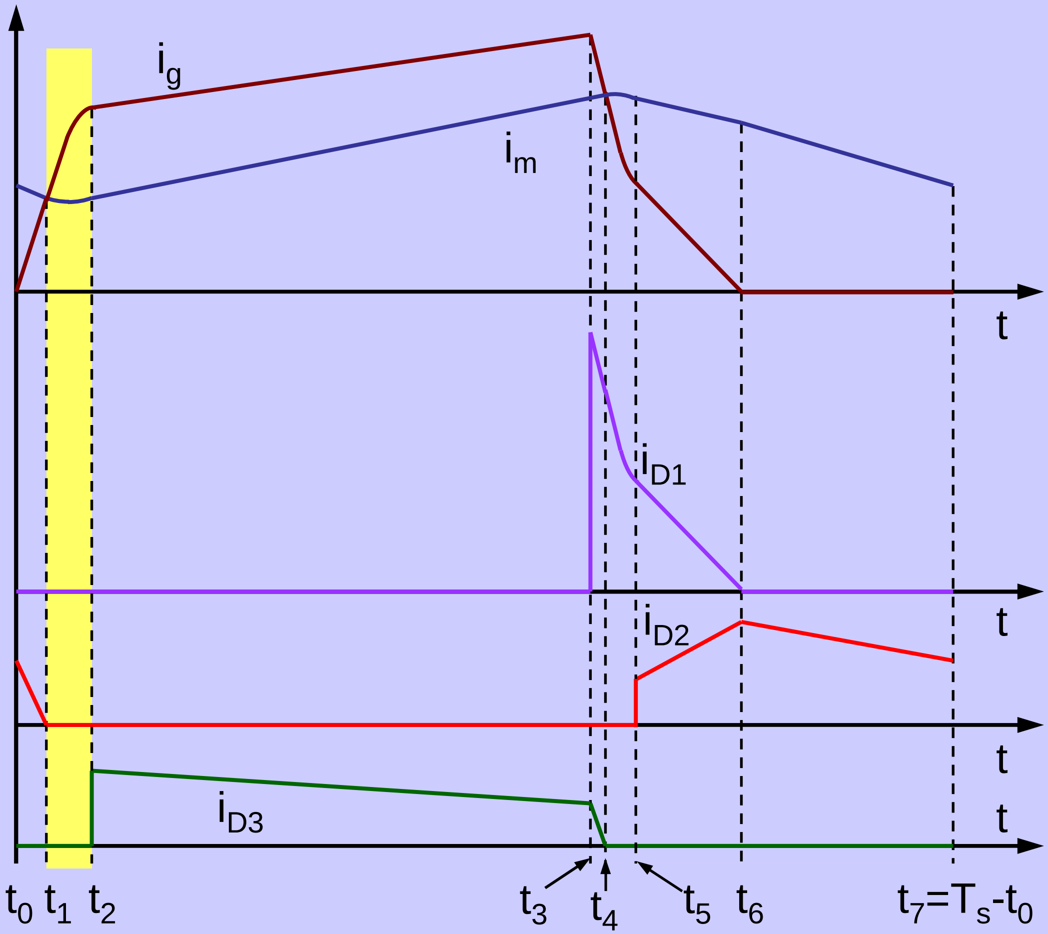
Modified IBF Converter



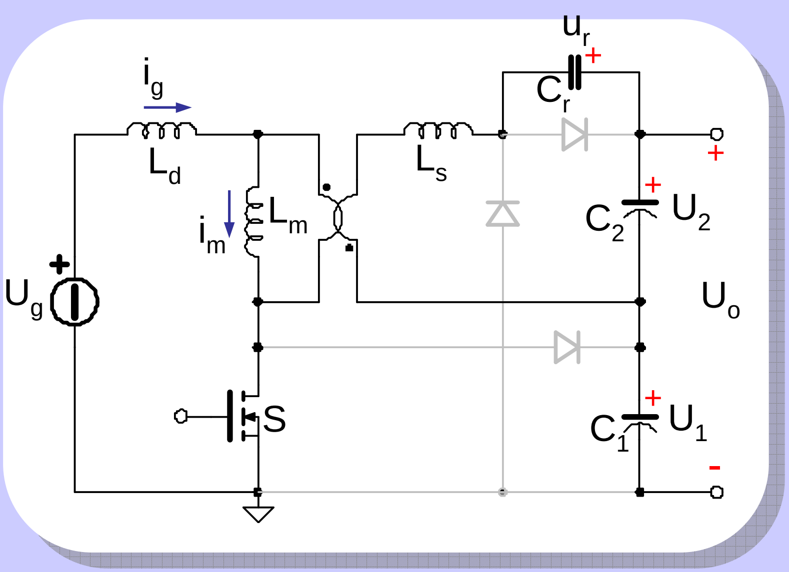
Interval $T_{01} = t_1 - t_0$



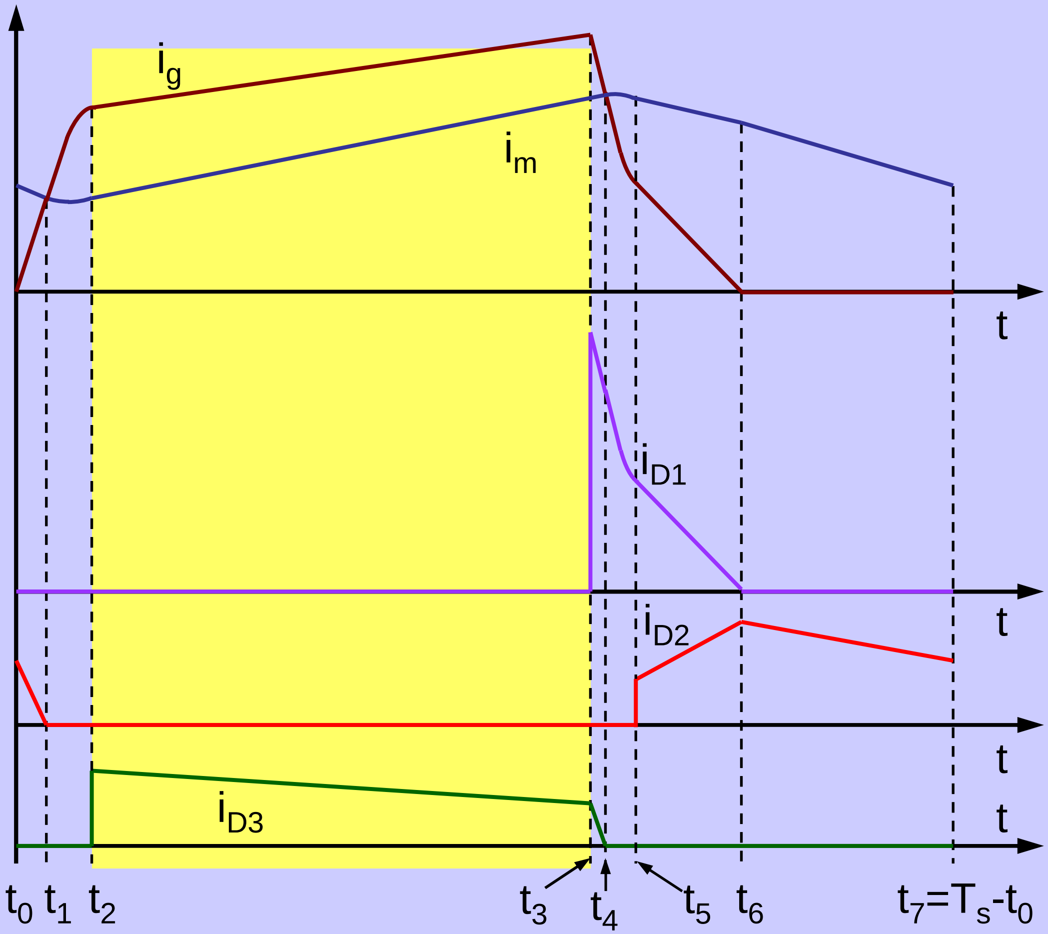
Modified IBF Converter



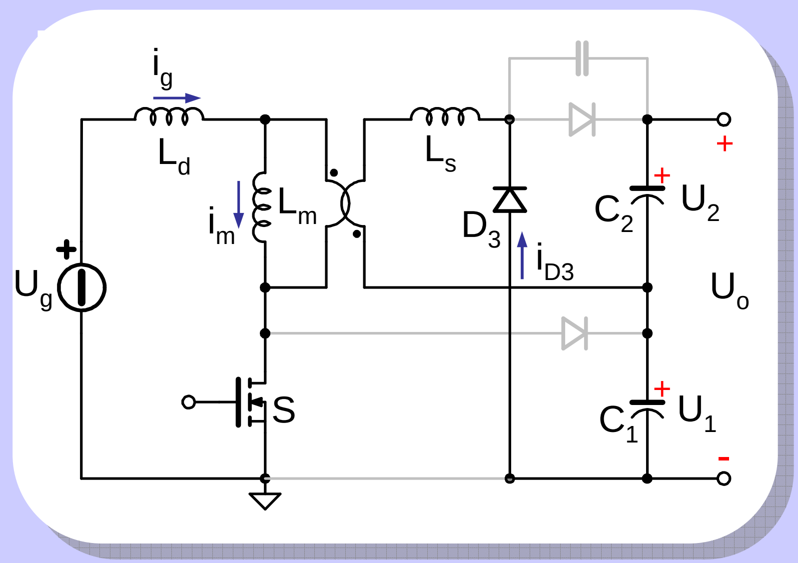
Interval $T_{12} = t_2 - t_1$



Modified IBF Converter

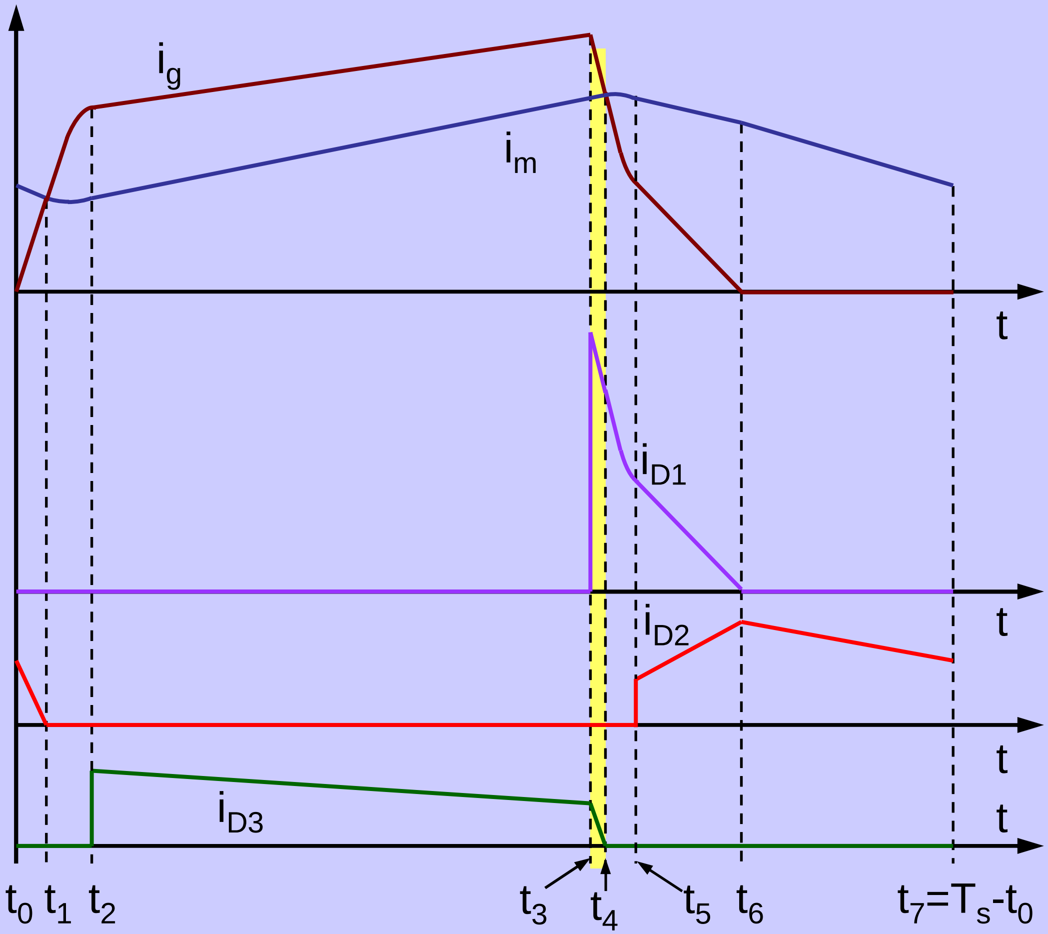


Interval $T_{23} = t_3 - t_2$

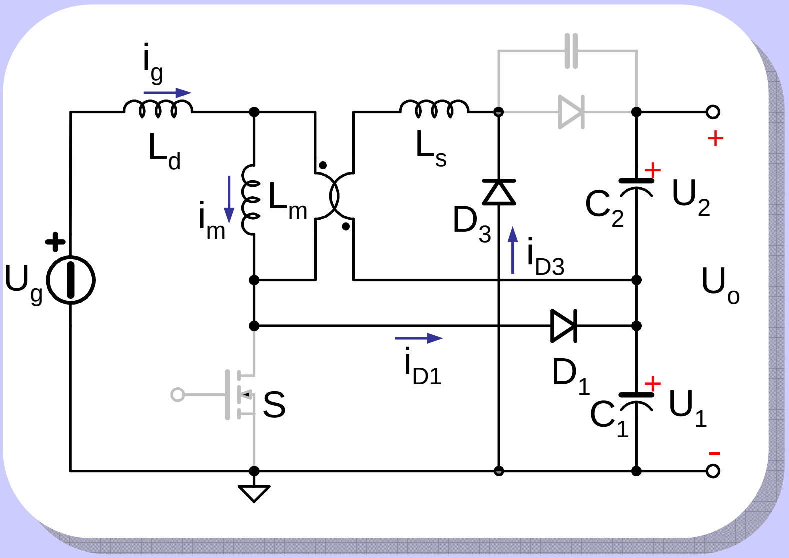


Note: actual i_{D3} slope can be either positive or negative

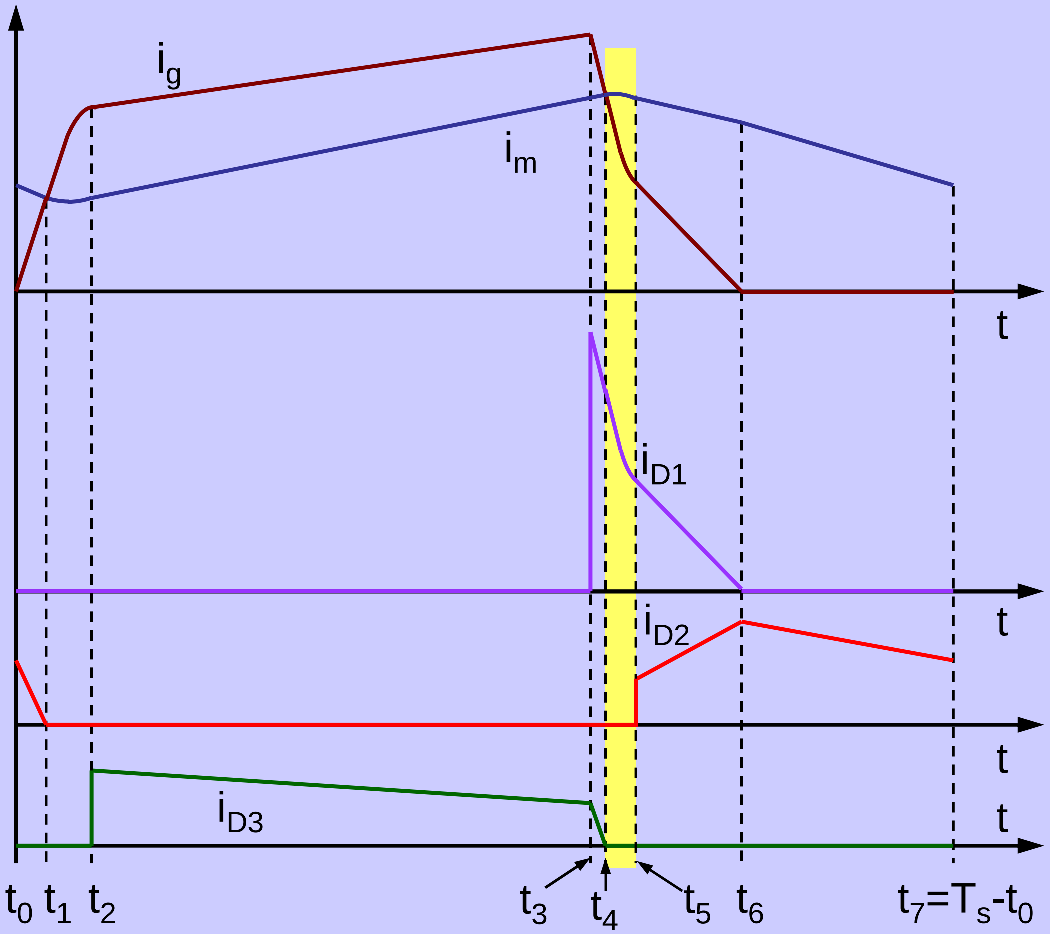
Modified IBF Converter



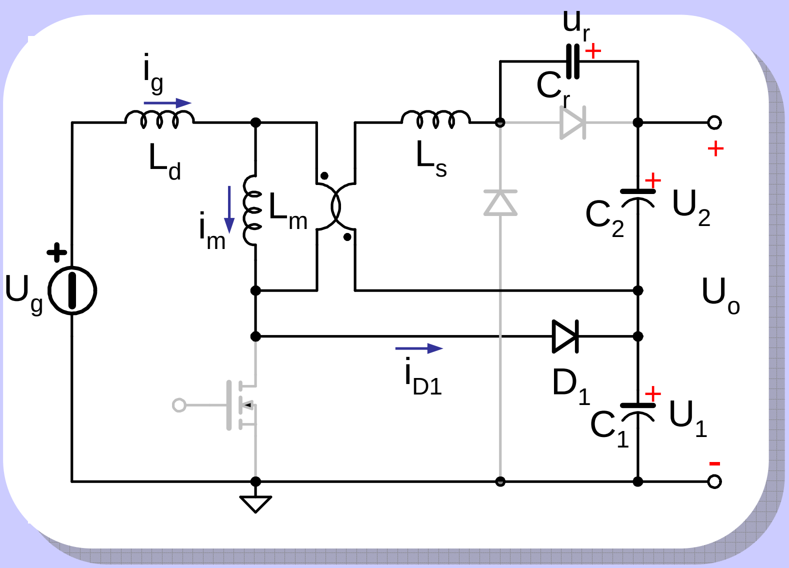
Interval $T_{34} = t_4 - t_3$



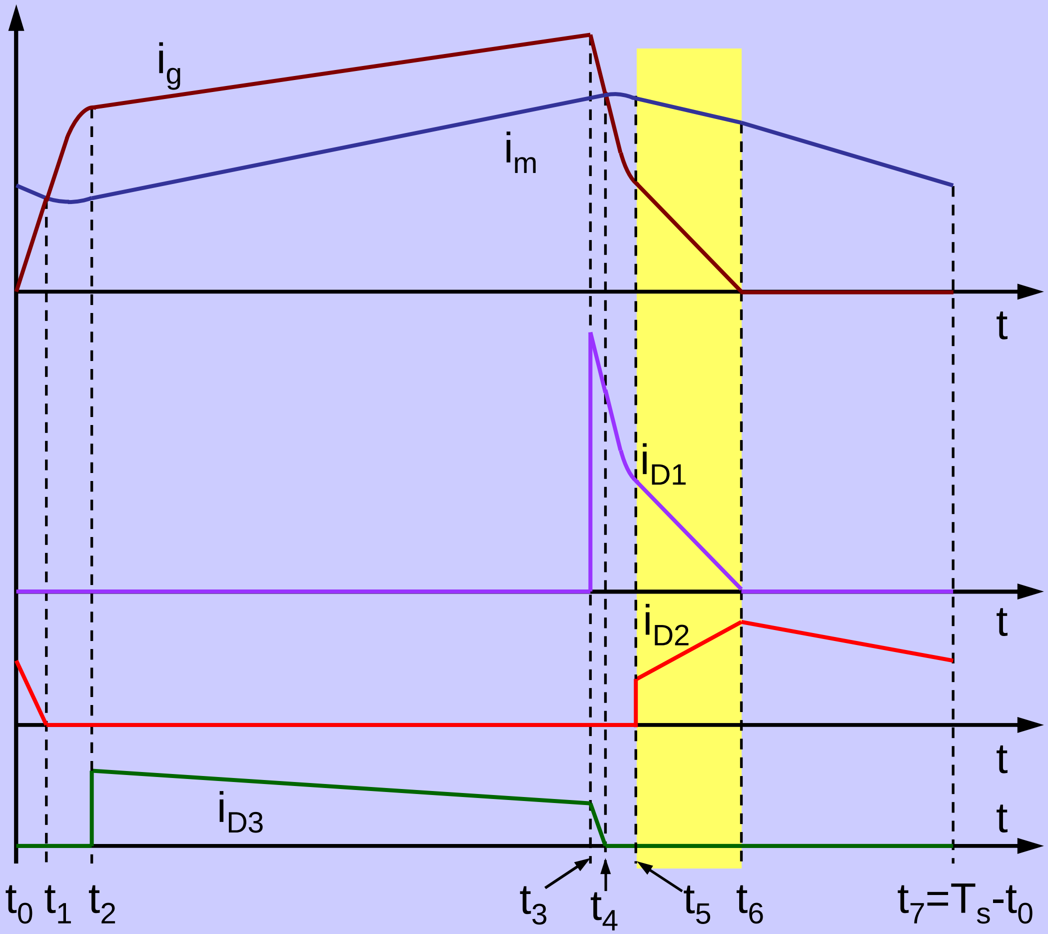
Modified IBF Converter



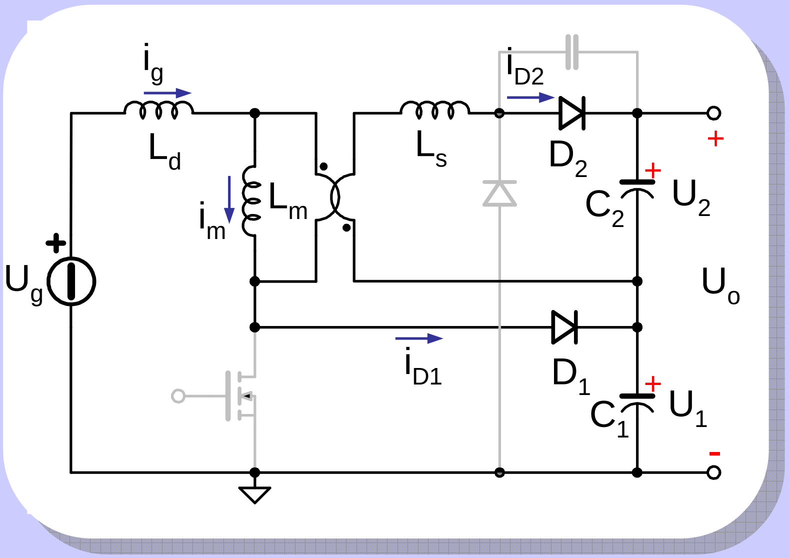
Interval $T_{45} = t_5 - t_4$



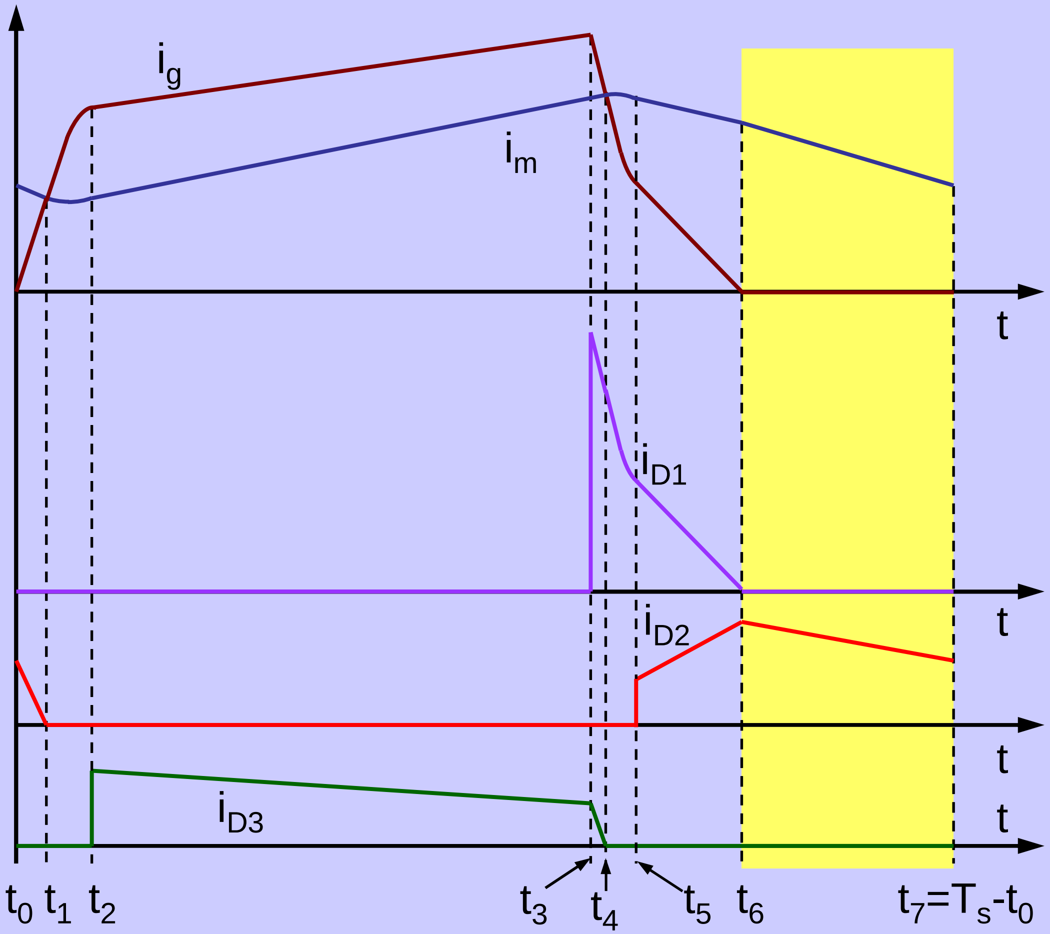
Modified IBF Converter



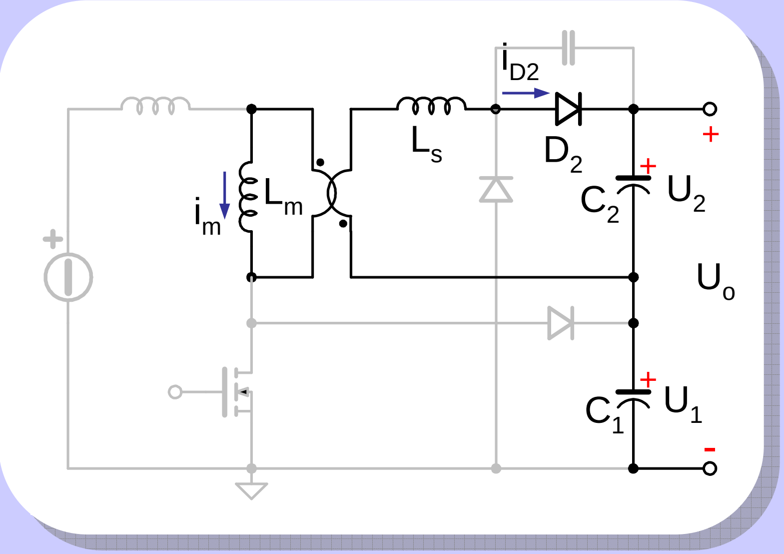
Interval $T_{56} = t_6 - t_5$



Modified IBF Converter



Interval $T_{67} = t_7 - t_6$



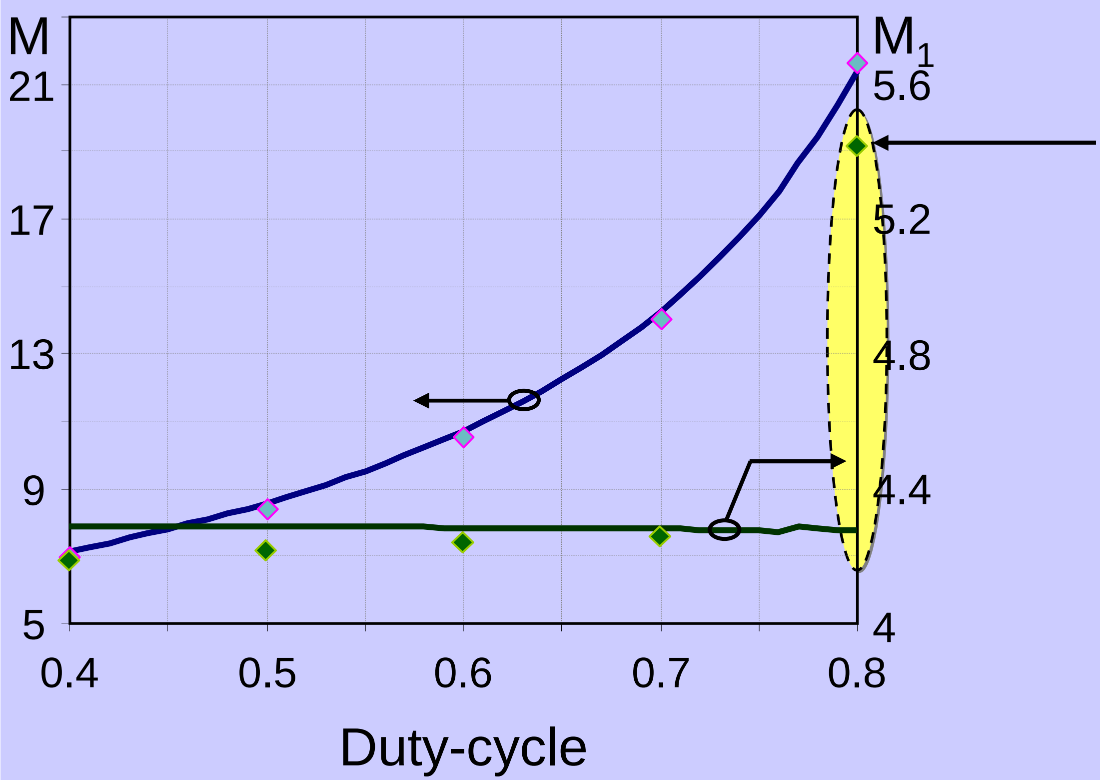
Converter Parameters

• Input voltage:	U_g = 25-35 V
• Output voltage:	U_o = 400 V
• Nominal output power:	P_o = 300 W
• Switching frequency:	f_s = 100 kHz
• Magnetizing inductance:	L_m = 20 μH
• Primary leakage inductance:	L_d = 0.4 μH
• Secondary leakage inductance:	L_s = 2 μH

Voltage Conversion Ratio

Comparison between calculations and spice simulations

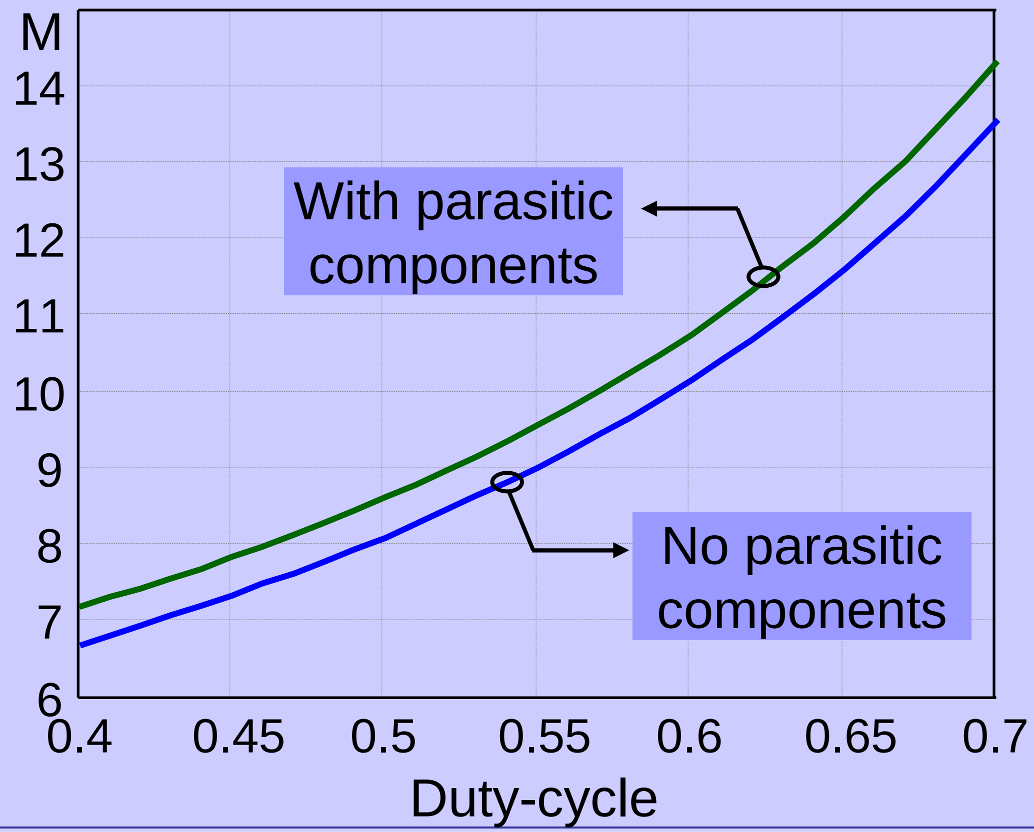
$$M = \frac{U_o}{U_g} \qquad M_1 = \frac{U_1}{U_g}$$



This unmatched point corresponds to a different topological sequence

Voltage Conversion Ratio

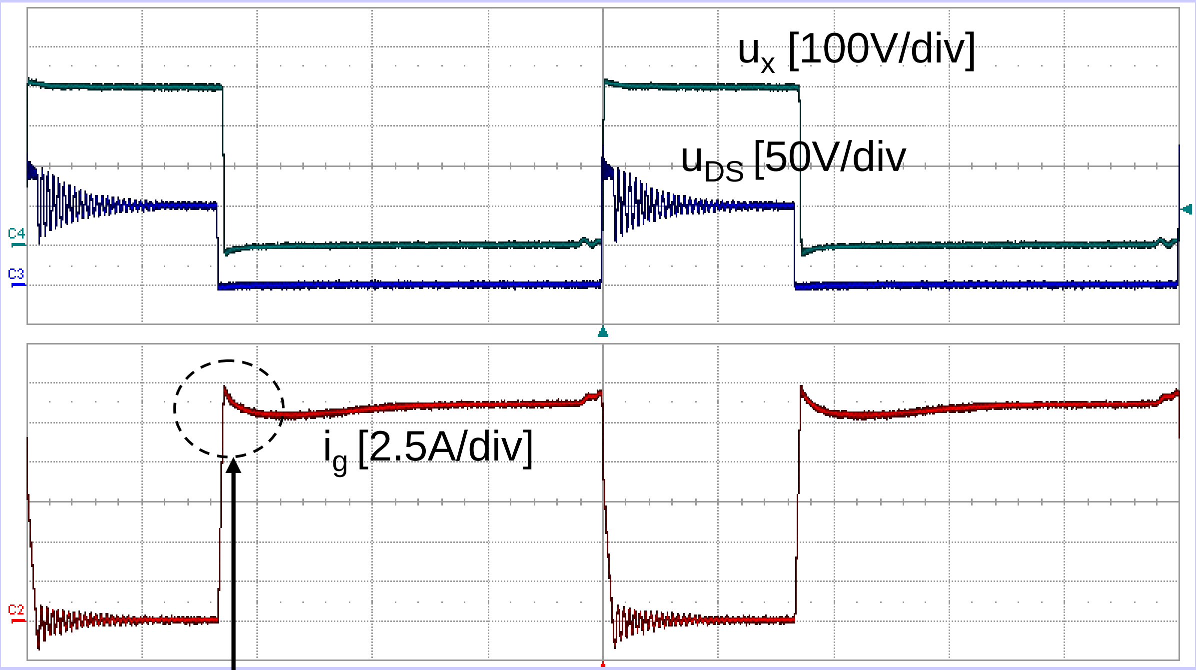
Effect of resonant intervals on the overall voltage gain



$$M = \frac{U_o}{U_g}$$

Experimental Results

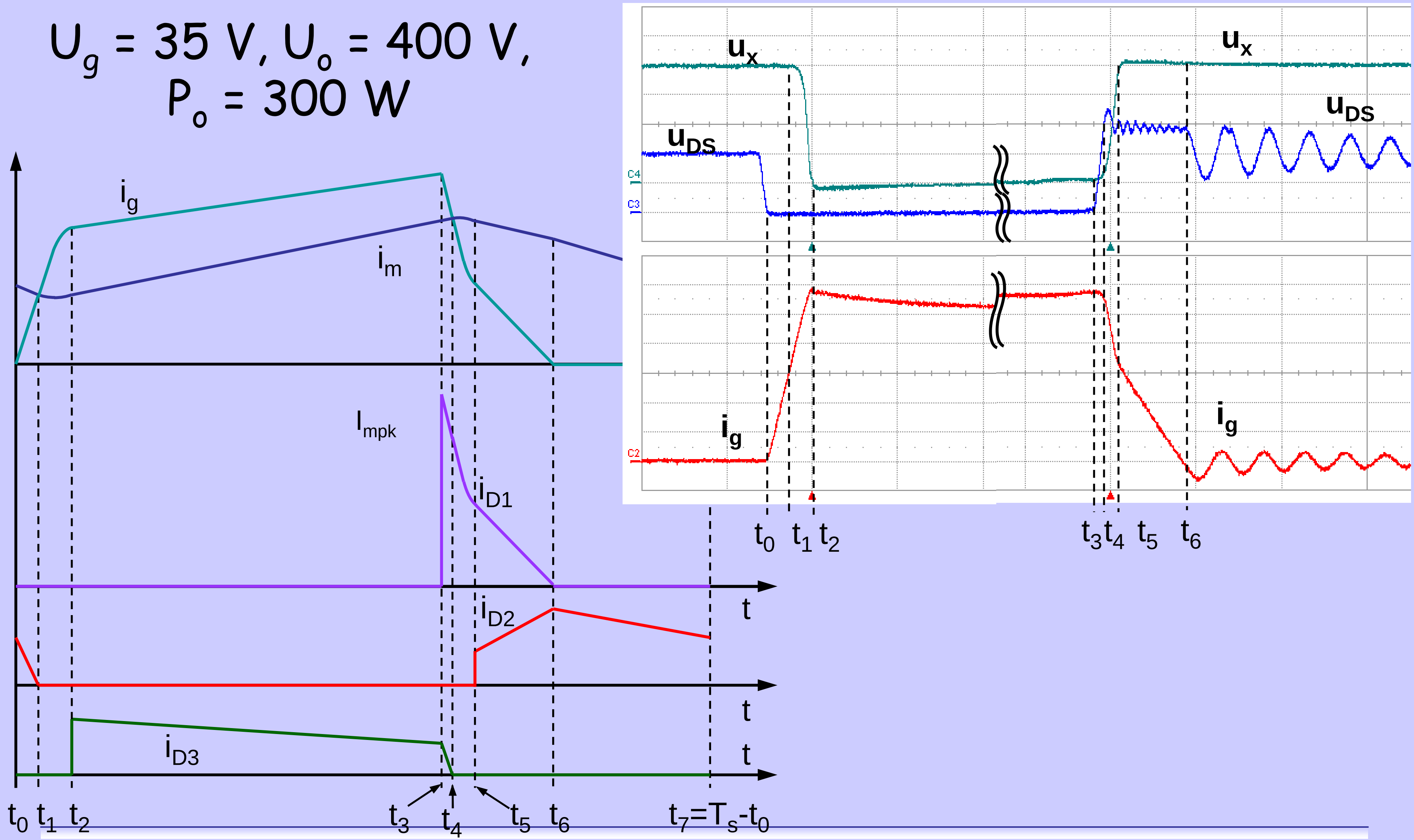
U_g = 35 V, U_o = 400 V, P_o = 300 W



Peaking due to a small dip in the converter input voltage due to fast current rise time

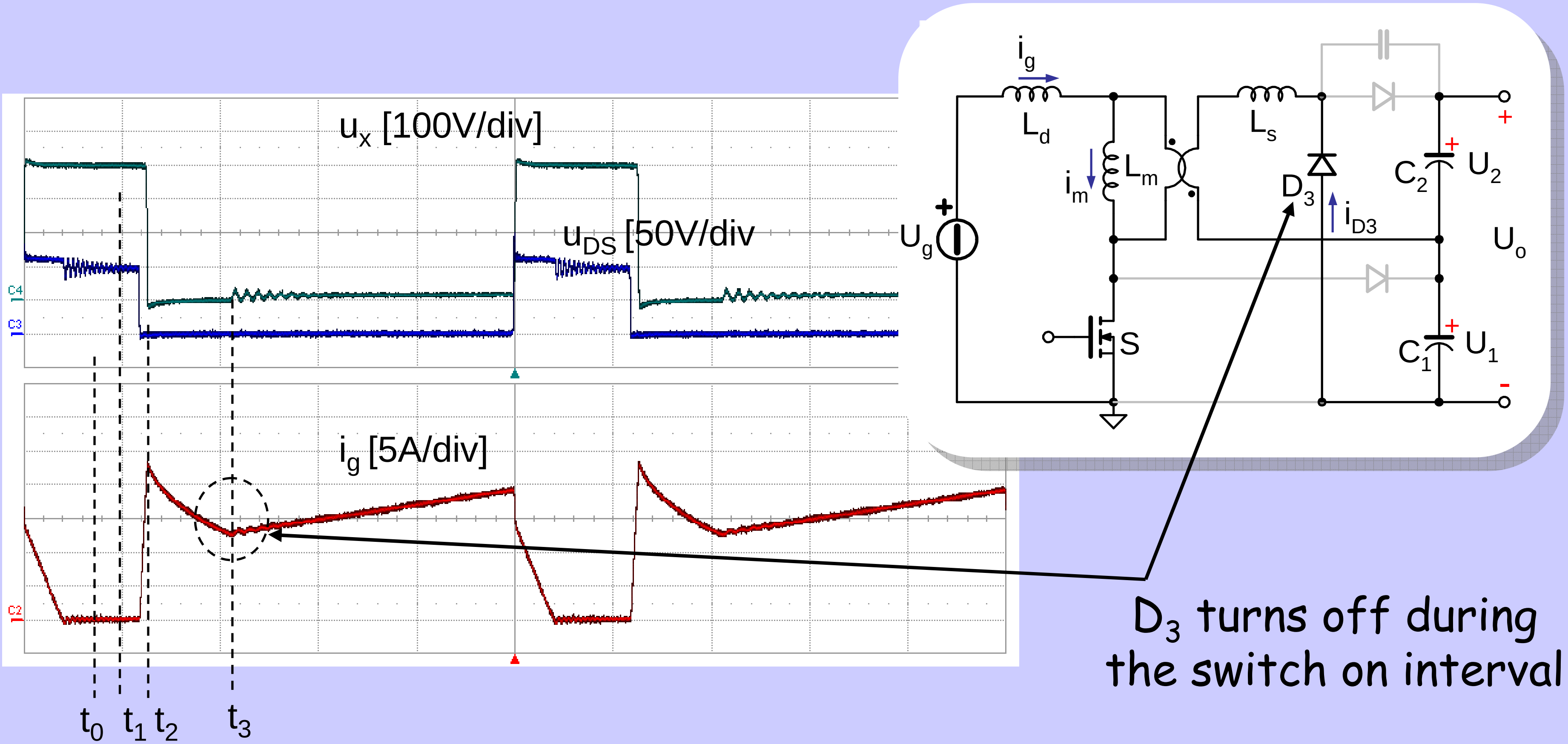
Experimental Results

U_g = 35 V, U_o = 400 V,
P_o = 300 W



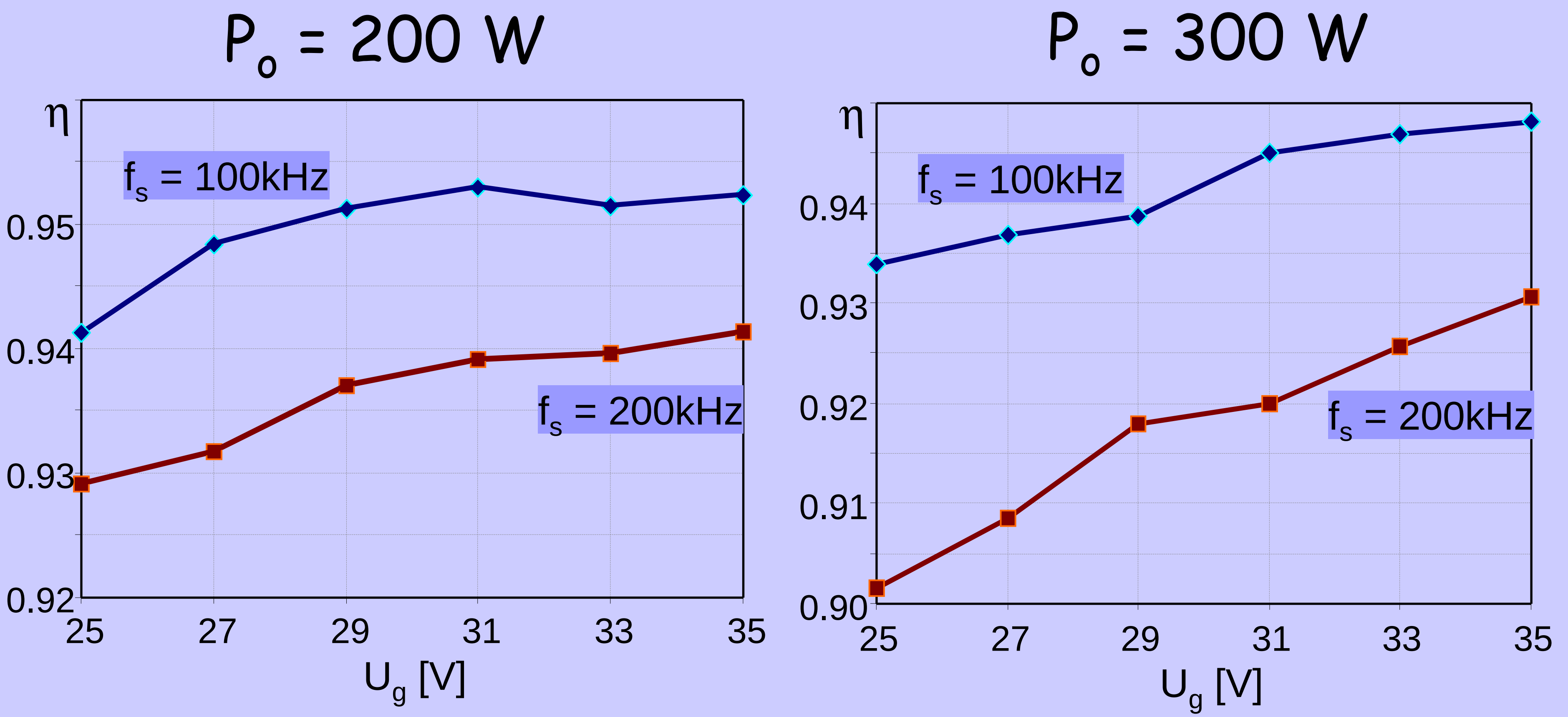
Experimental Results

$U_g = 25\ V,\ U_o = 400\ V,\ P_o = 300\ W$



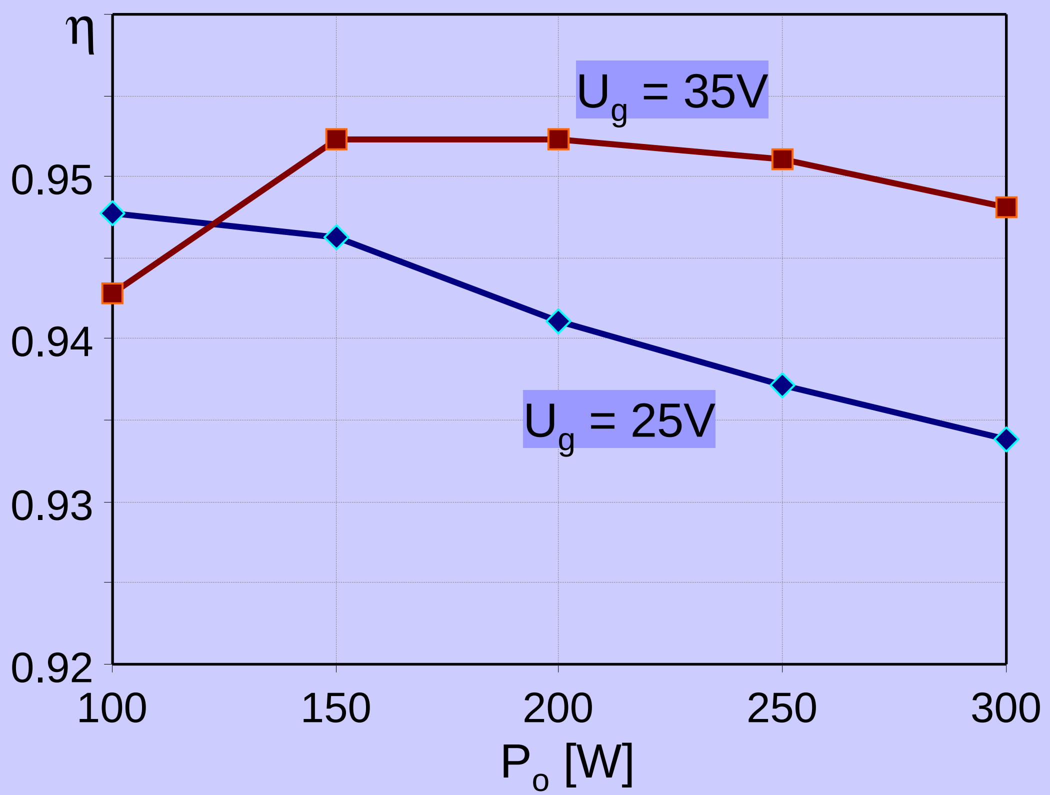
D₃ turns off during the switch on interval

Measured Efficiency



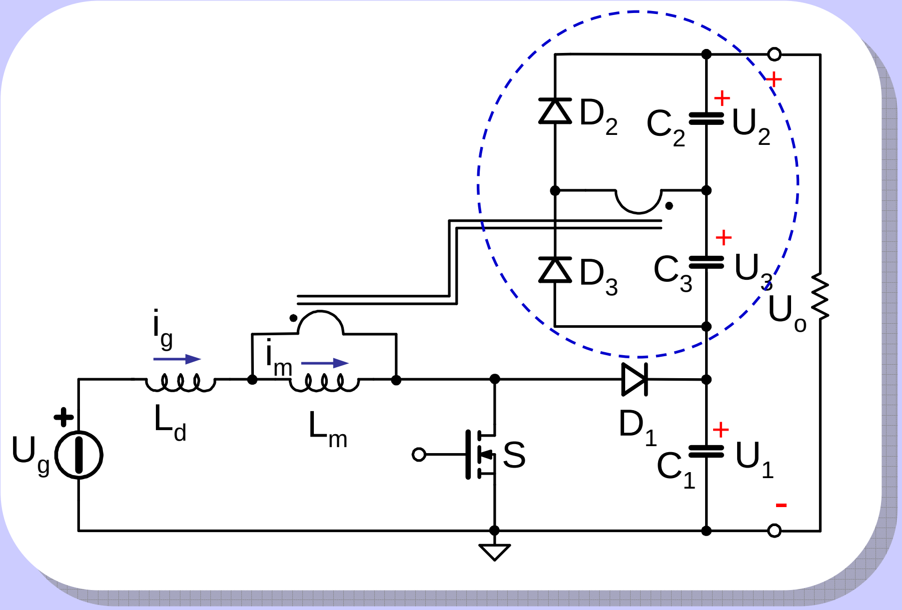
Measured Efficiency

f_s = 100 kHz



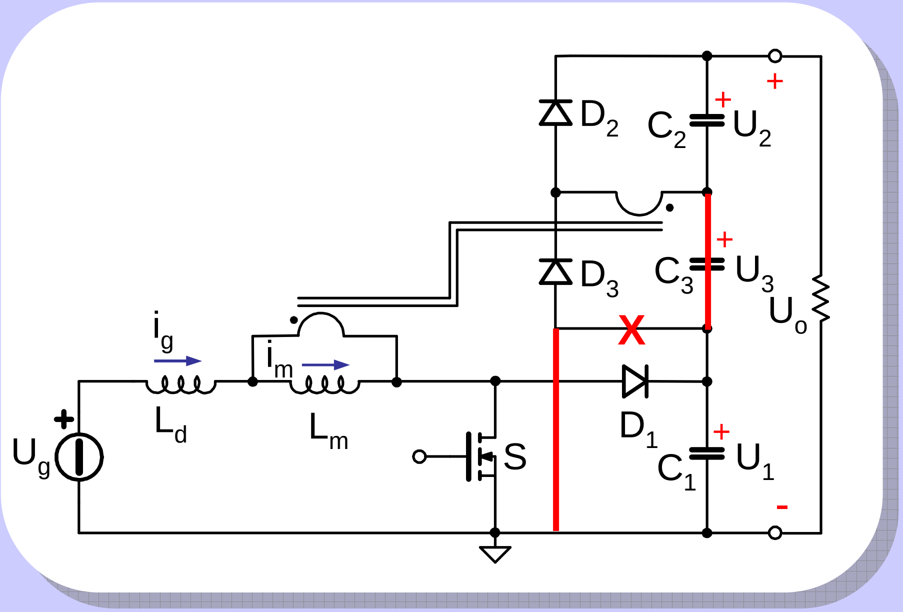
IBF Converter with Voltage Multiplier

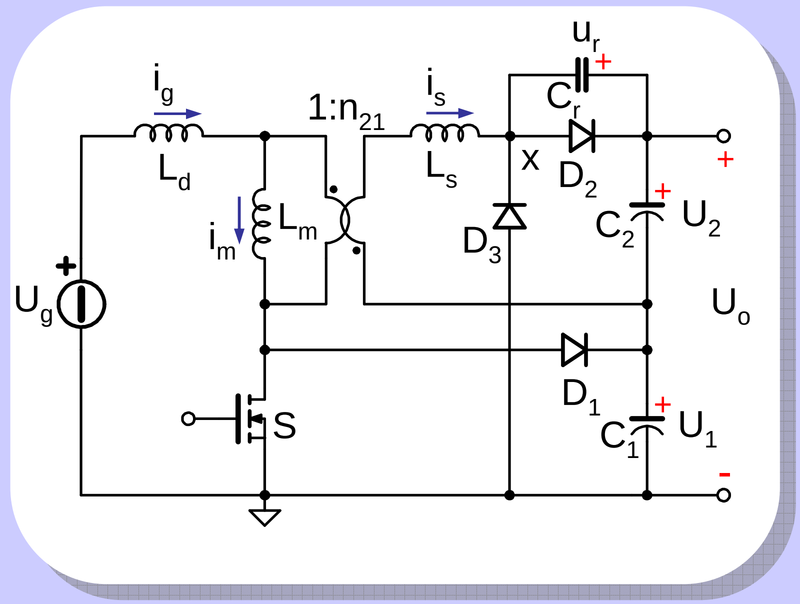
Voltage multiplier cell



IBF Converter with Voltage Multiplier

IBF converter with voltage multiplier cell
versus modified IBF

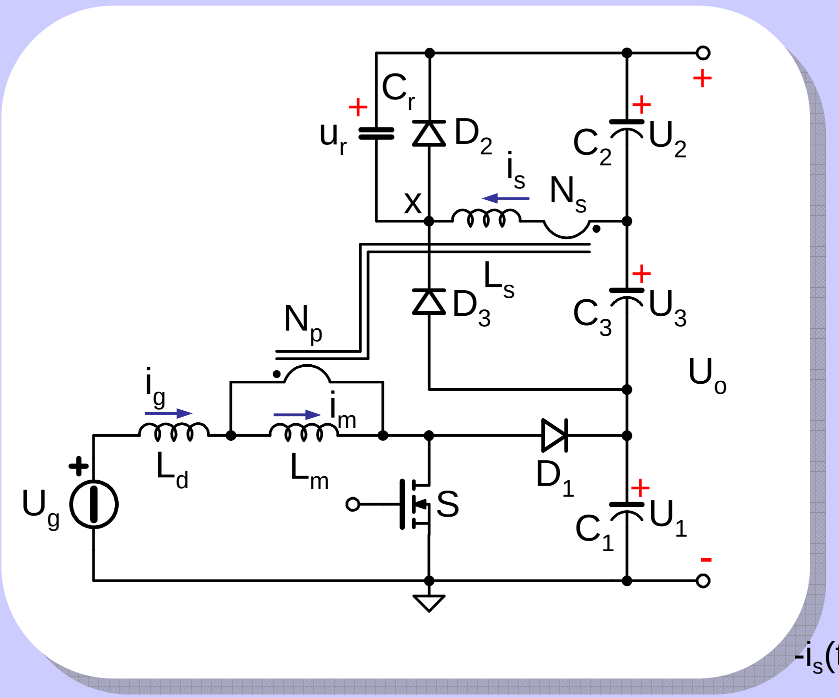


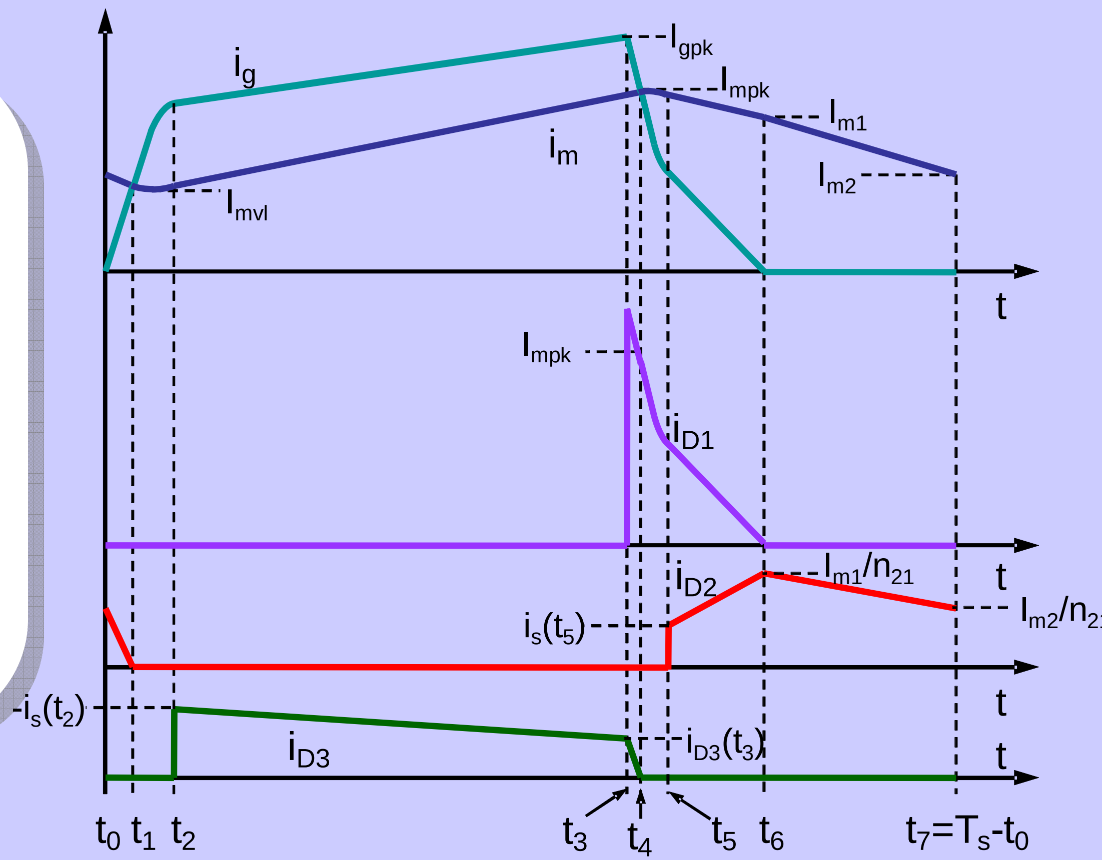


Similar behavior with a higher degree of freedom
in controlling the switch voltage stress

Converter Waveforms

BOOST section in DCM and FLYBACK section in CCM





Experimental Prototype

Design example:

Input voltage:
U_g = 25÷35V
Output voltage:
U_o = 400V
Nominal output power:
P_o = 300W
Switching frequency:
f_s = 100kHz
Boost output: → 150V rated mosfet
U_1 = 75V
Magnetizing inductance:
L_m = 20μH
Primary leakage inductance:
L_d = 0.4μH
Secondary leakage inductance:
L_s = 2μH

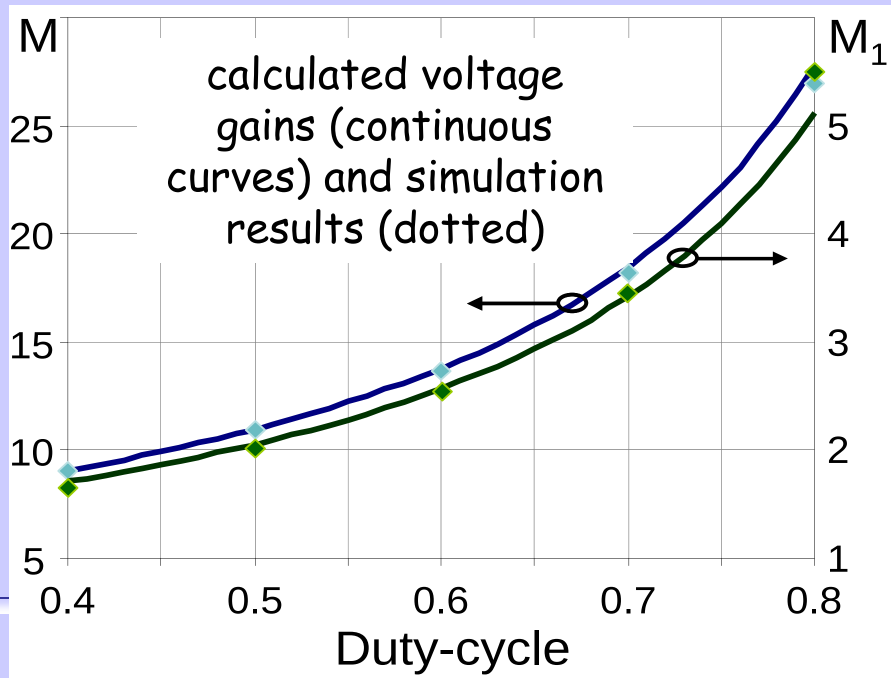
Based on desired current ripple and DCM-CCM mode at nominal power

From the design constraints:

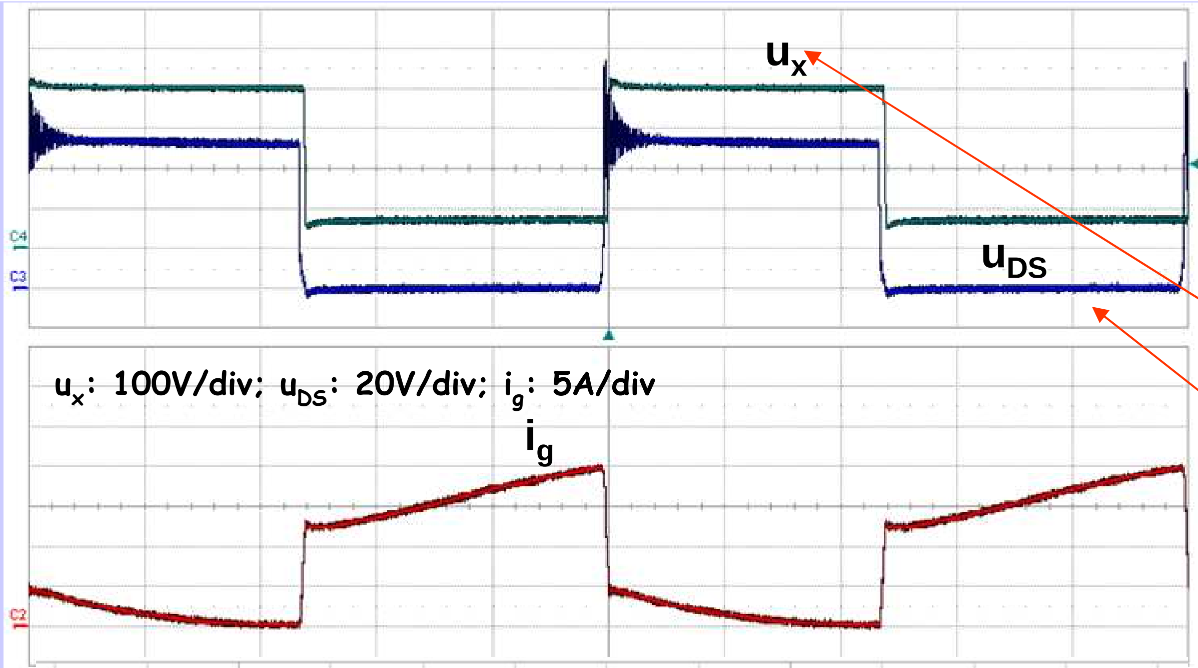
$M = U_o / U_g = 400/35 = 11.42$
$M_1 = U_1 / U_g = 75/35 = 2.143$

Numerically solving:

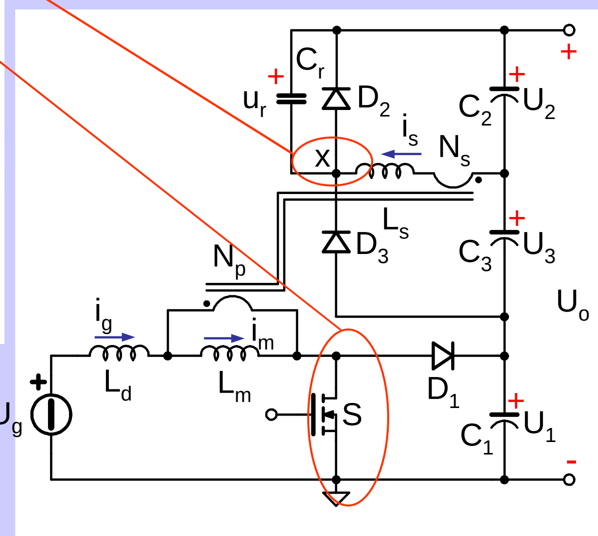
$d = 0.519$, $n_{21} = 4.589$
$M_2 = U_2 / U_g = 4.823$
$M_3 = M - M_1 - M_2 = U_3 / U_g = 4.454$

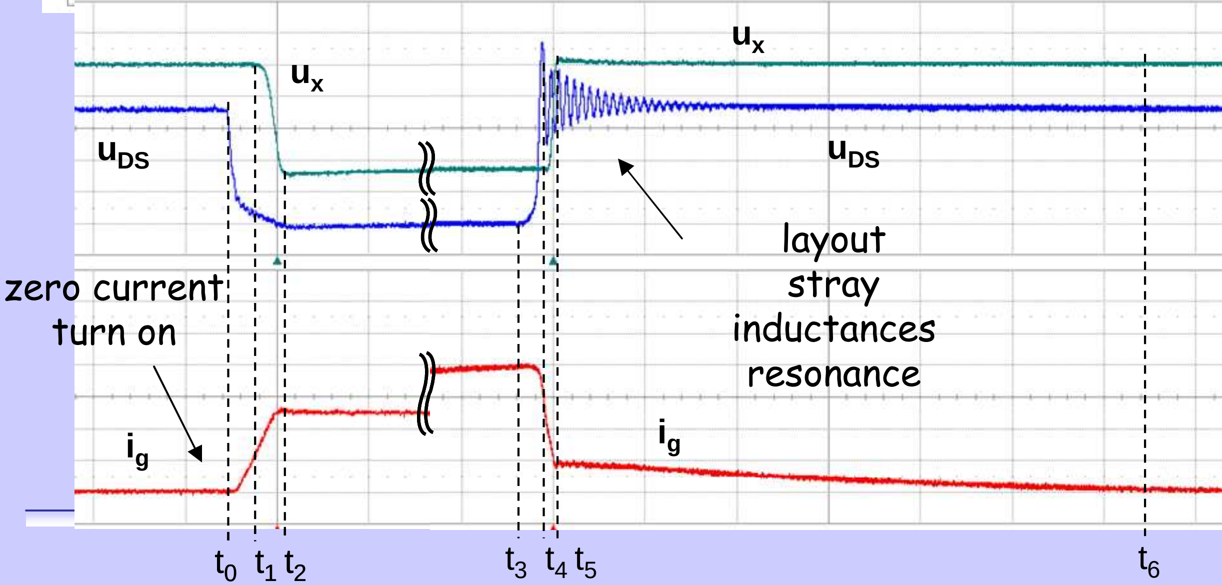


Experimental results



Measured main waveforms in a switching period
U_g = 35V, V_o = 400V, P_o = 300W





Details of turn on and turn off intervals

Converter efficiency

The converter efficiency was measured as a function of input voltage, at P_o=300W,Fig.1, and at U_g=[25V,35V] and variable output power, Fig. 2

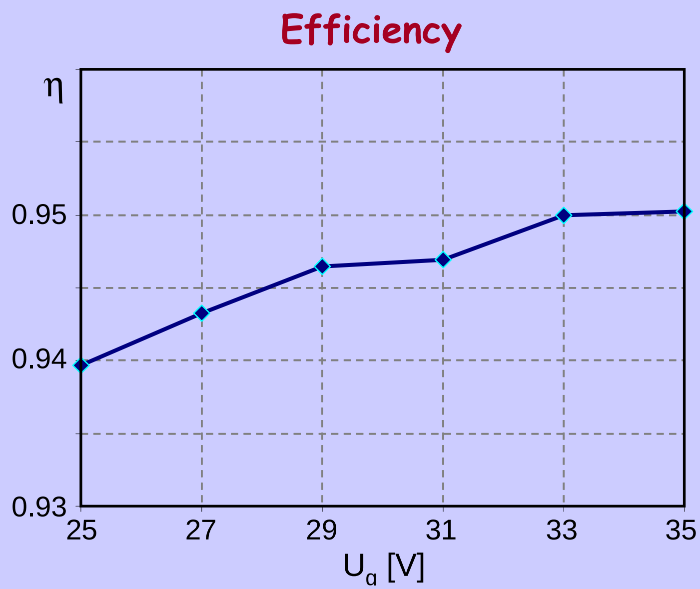


Fig.1

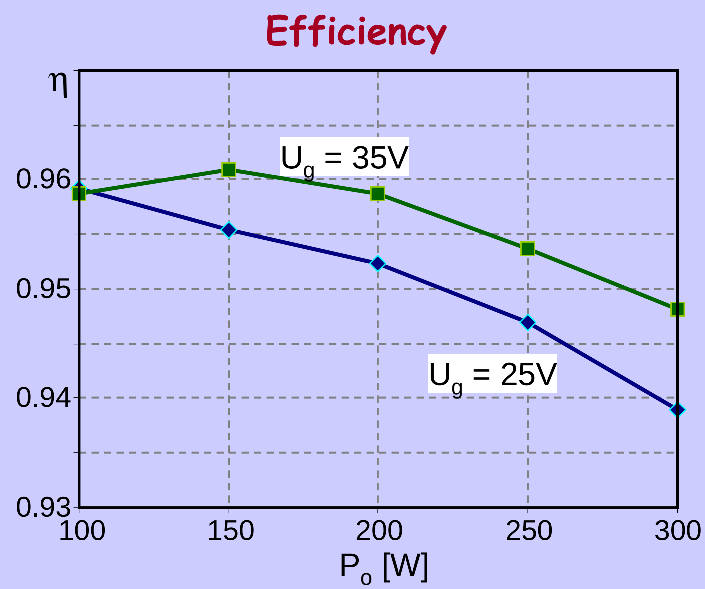
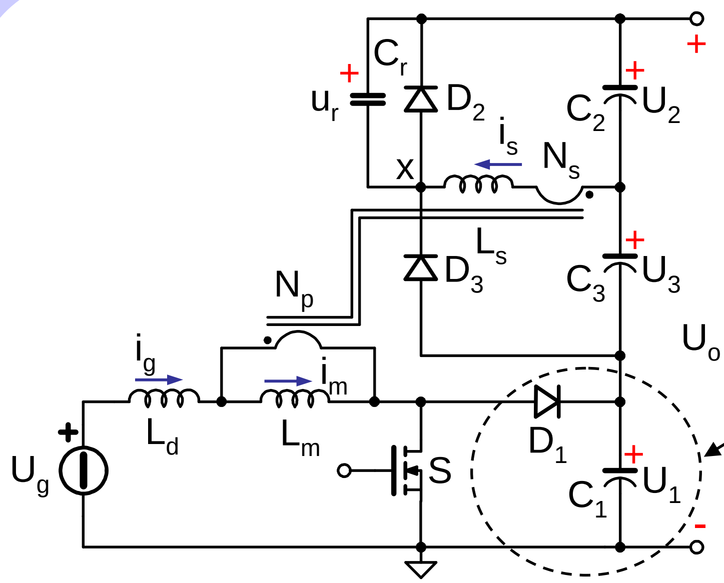
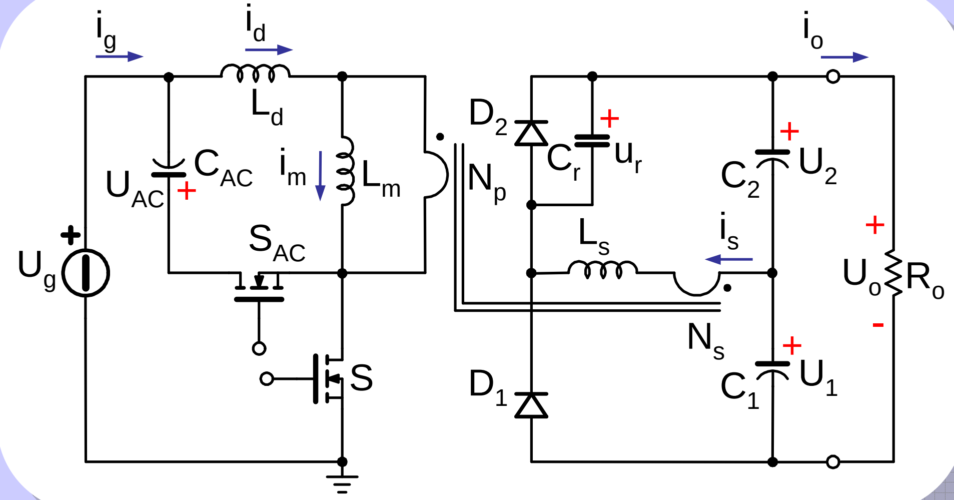


Fig.2

Isolated IBF Converter



For **isolation**, the loss-less snubber D_1-C_1 is substituted by an **active clamp**



Isolated IBF Converter

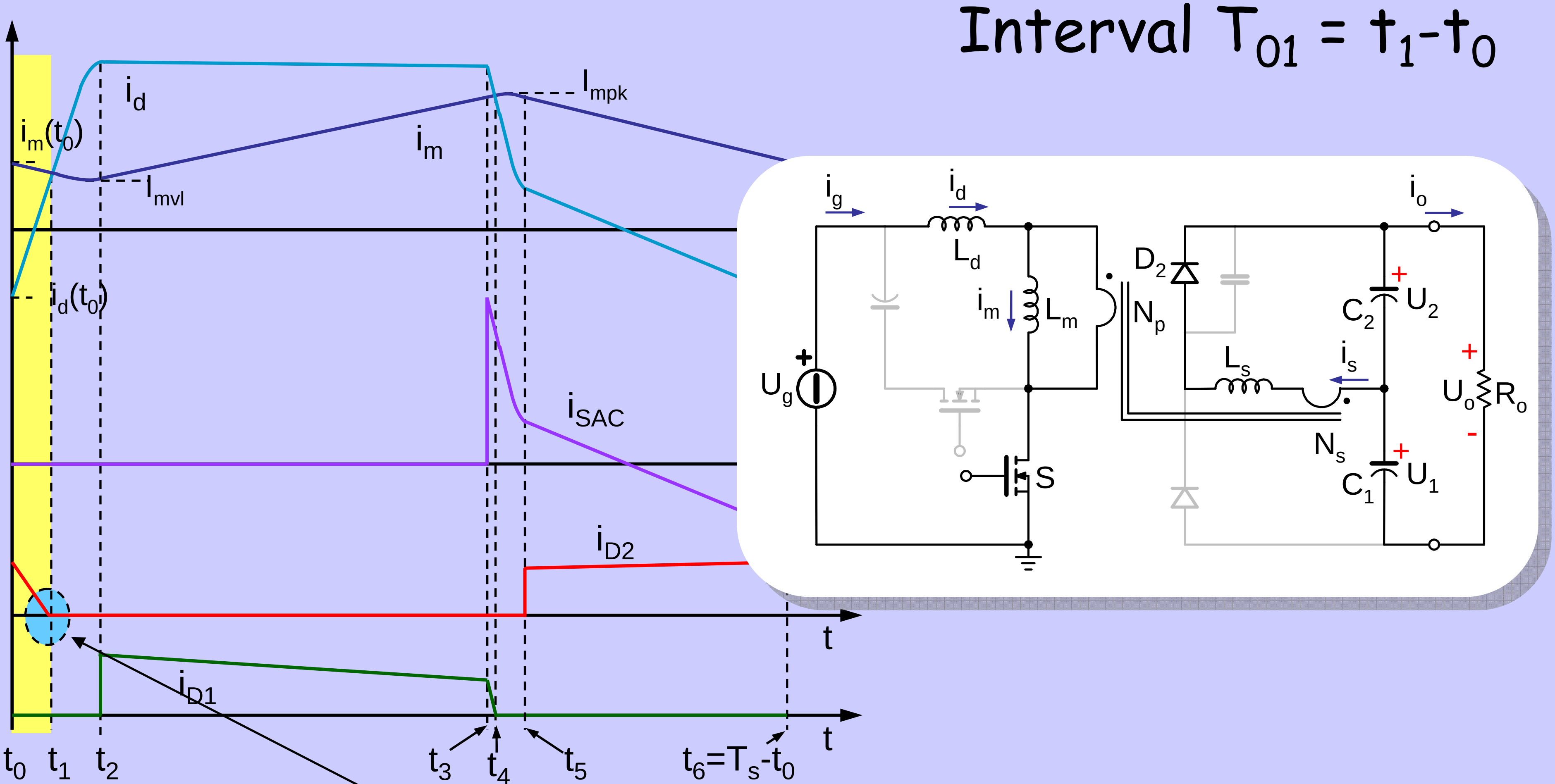
Advantages:

- ZVS turn on
- Soft diode turn off
- Reduces switch voltage stress
- Clean diode voltage waveforms without parasitic oscillations
- Energy transfer toward the output also during switch turn on interval
- Reduced active clamp circulating current

Converter Operation

Hp: negligible capacitor voltage ripples

Interval $T_{01} = t_1 - t_0$

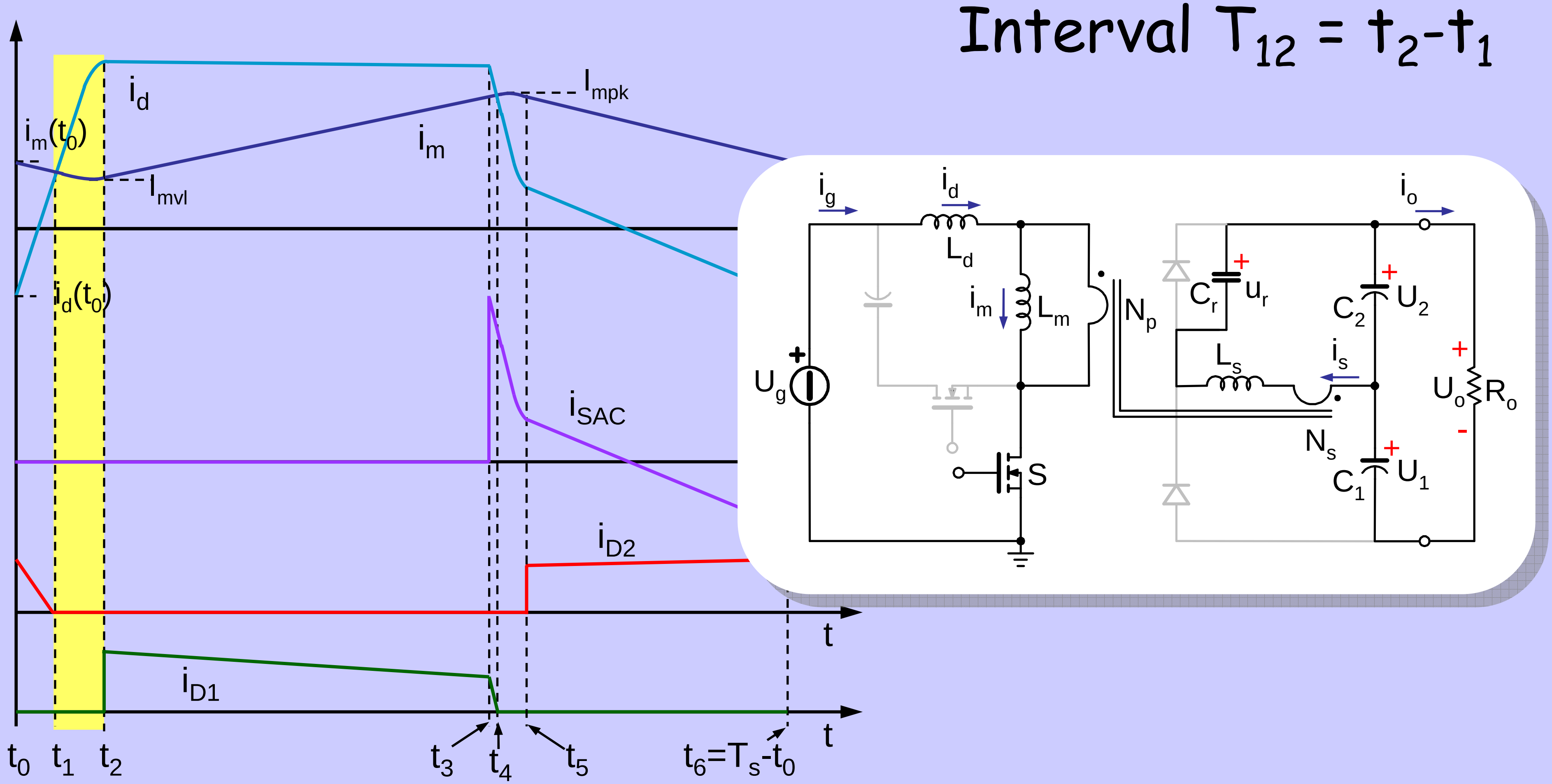


Soft D_2 turn off

Converter Operation

Hp: negligible capacitor voltage ripples

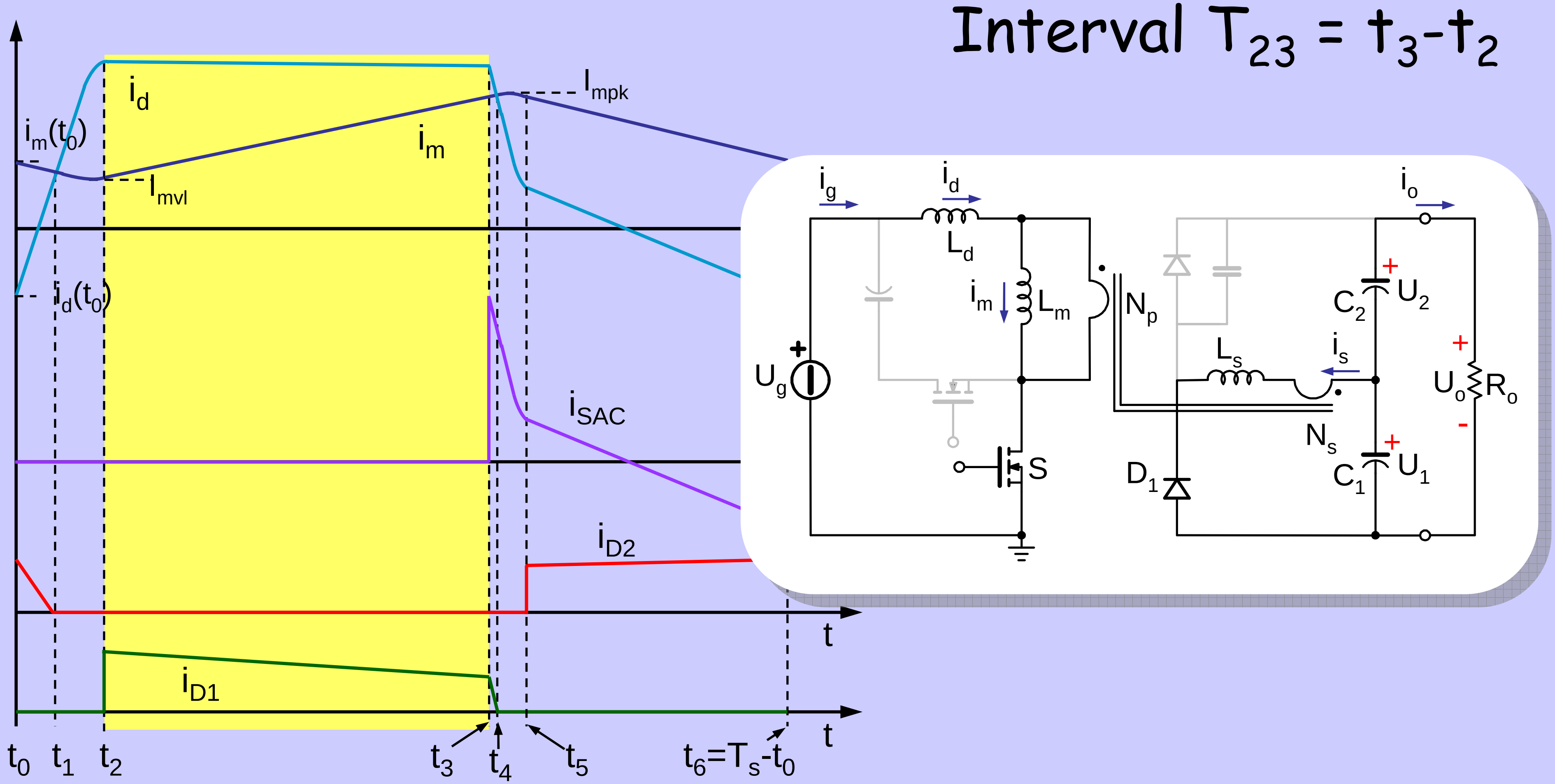
Interval $T_{12} = t_2 - t_1$



Converter Operation

Hp: negligible capacitor voltage ripples

Interval $T_{23} = t_3 - t_2$

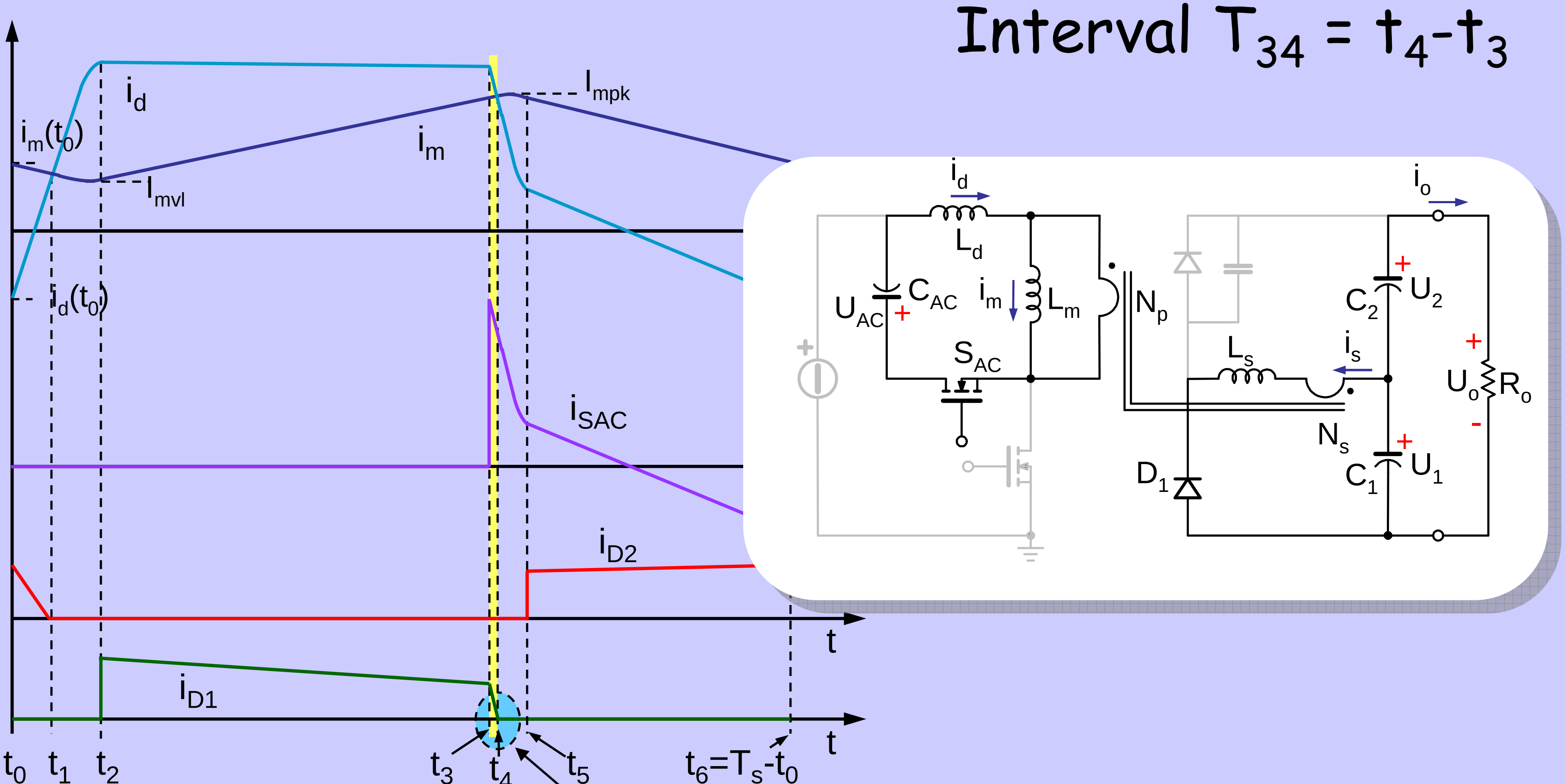


Note: actual i_{D1} slope can be either positive or negative

Converter Operation

Hp: negligible capacitor voltage ripples

Interval $T_{34} = t_4 - t_3$

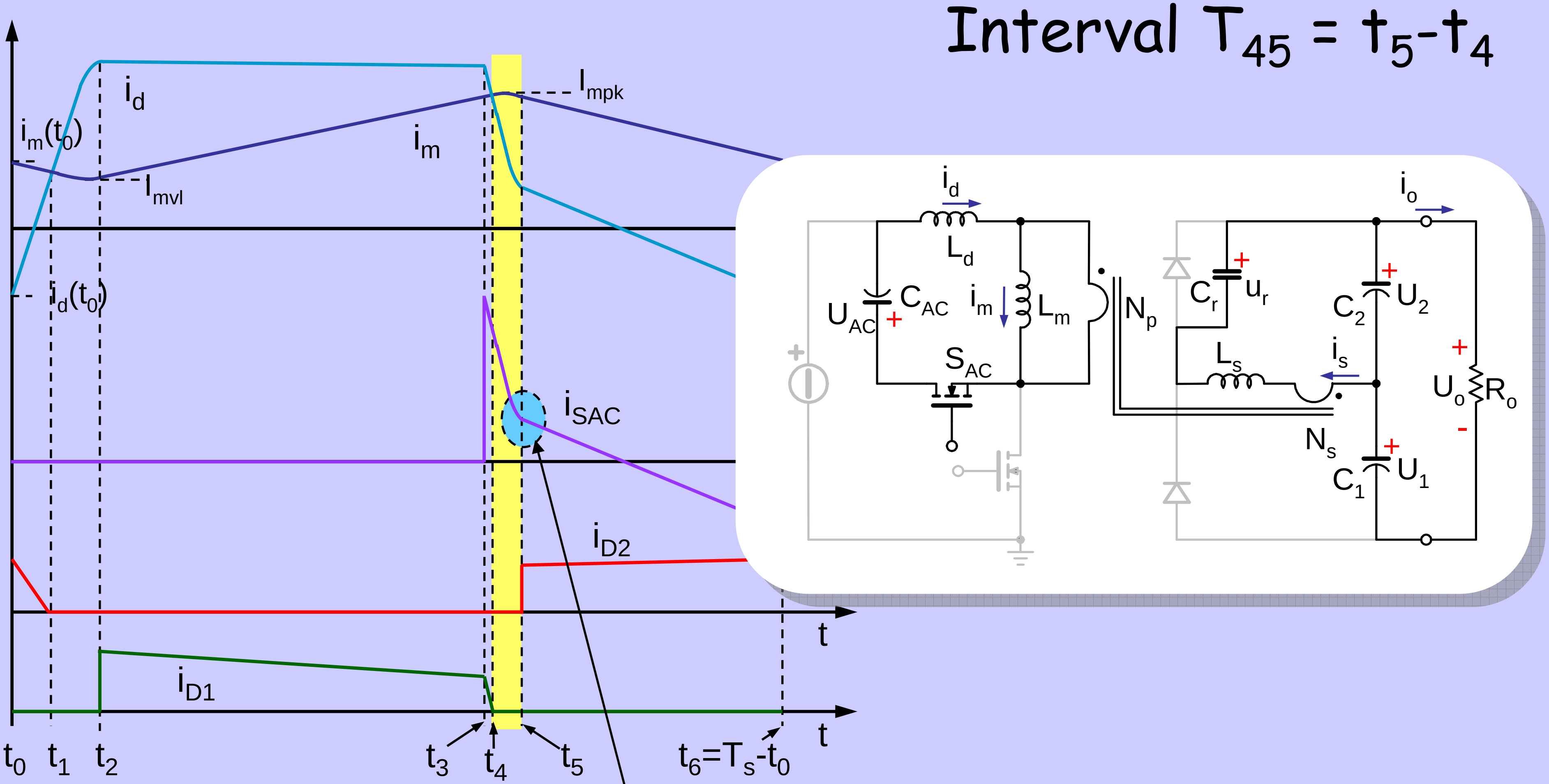


Soft D_1 turn off

Converter Operation

Hp: negligible capacitor voltage ripples

Interval $T_{45} = t_5 - t_4$

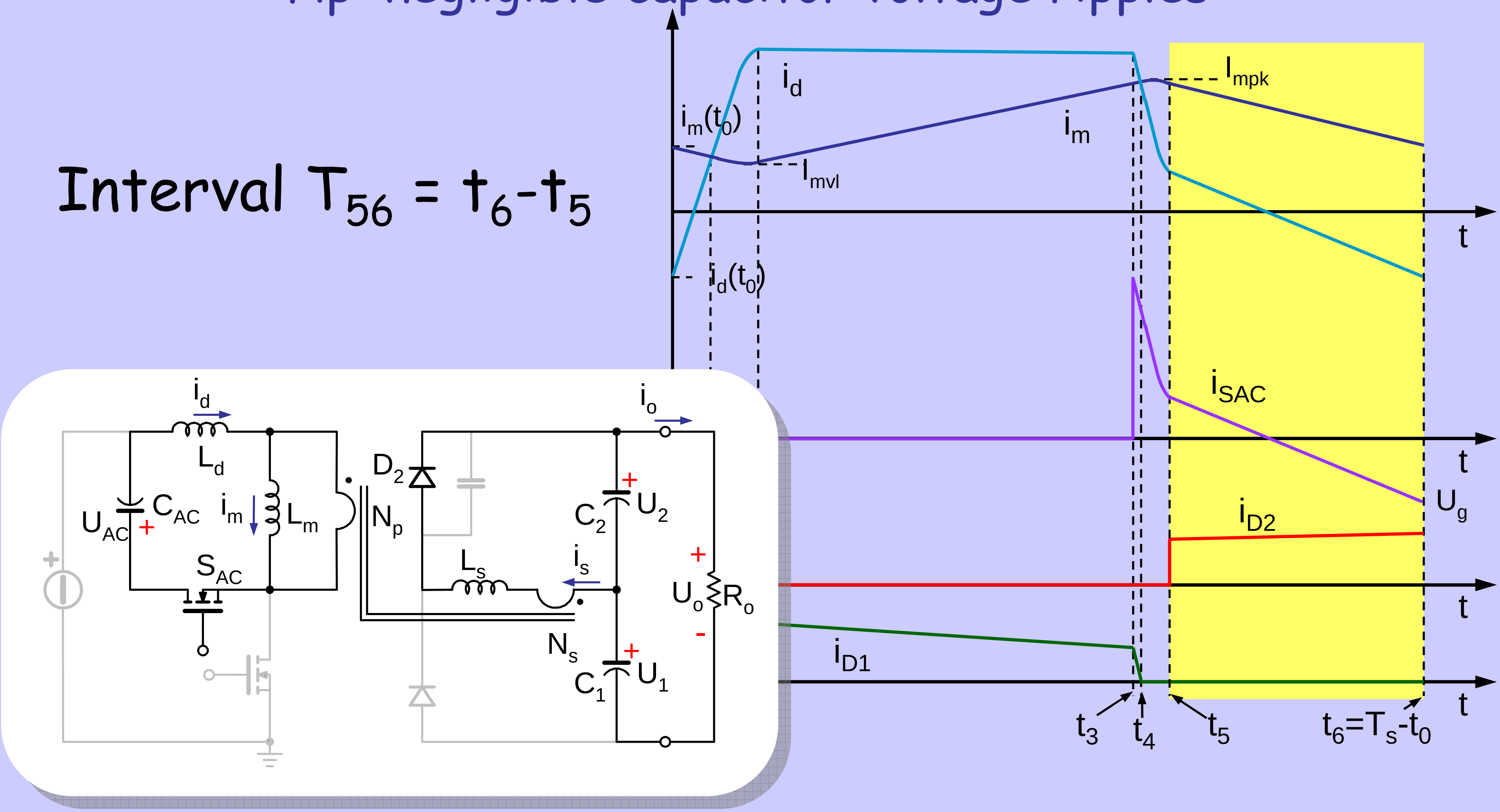


Reduced active clamp circulating current

Converter Operation

Hp: negligible capacitor voltage ripples

Interval $T_{56} = t_6 - t_5$

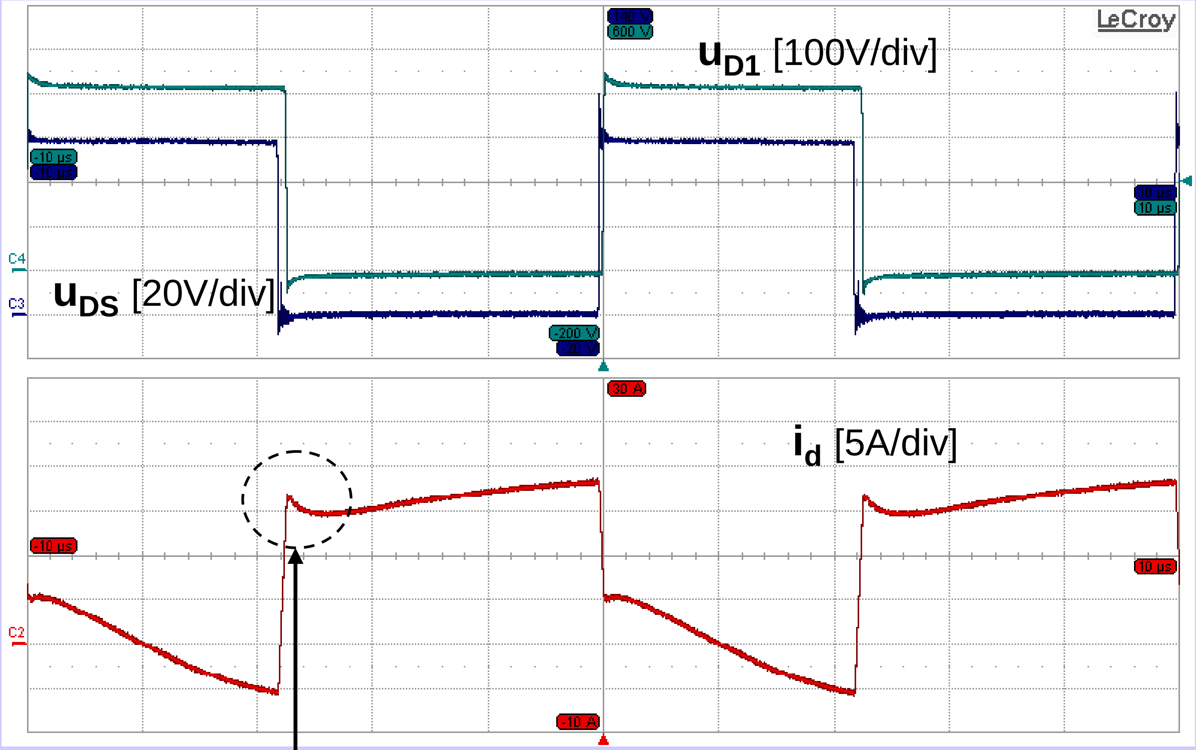


Converter Parameters

- Input voltage: U_g = 25-35 V
- Output voltage: U_o = 400 V
- Nominal output power: P_o = 300 W
- Switching frequency: f_s = 100 kHz
- Magnetizing inductance: L_m = 20 μH
- Primary leakage inductance: L_d = 0.4 μH
- Secondary leakage inductance: L_s = 2 μH

Experimental Results

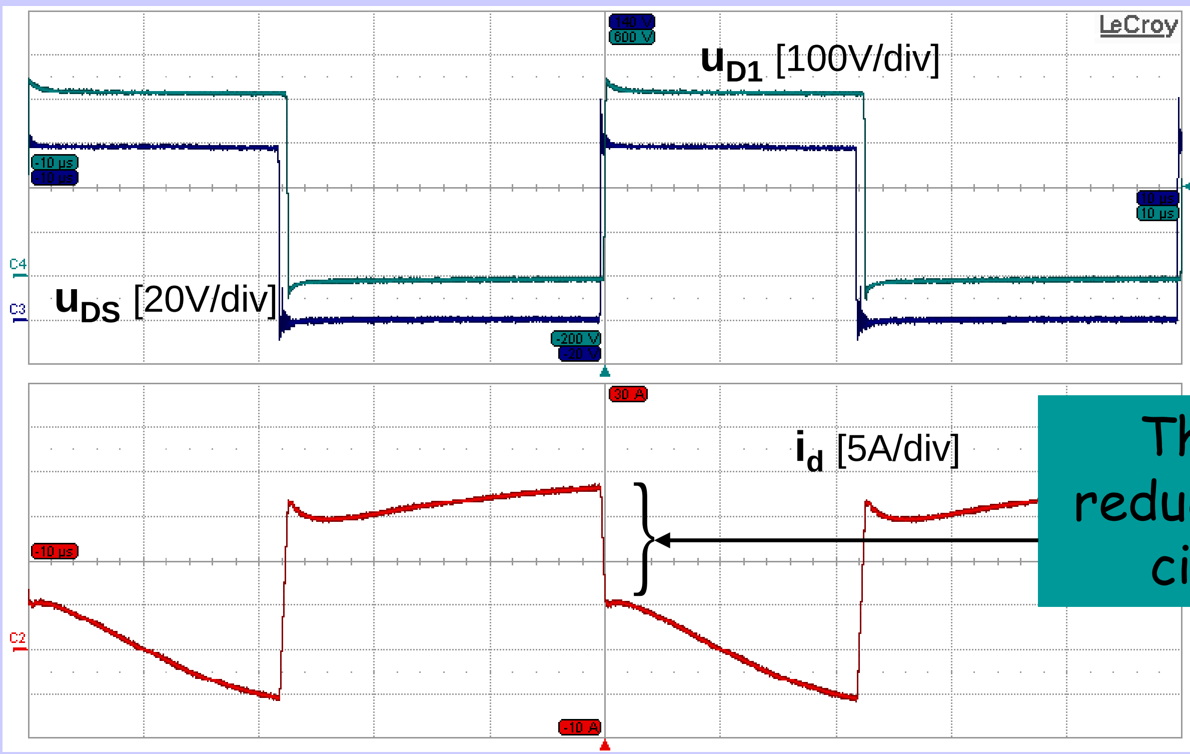
U_g = 35 V, U_o = 400 V, P_o = 300 W (2μs/div)



Peaking due to a small dip in the converter input voltage due to the fast current rise time

Experimental Results

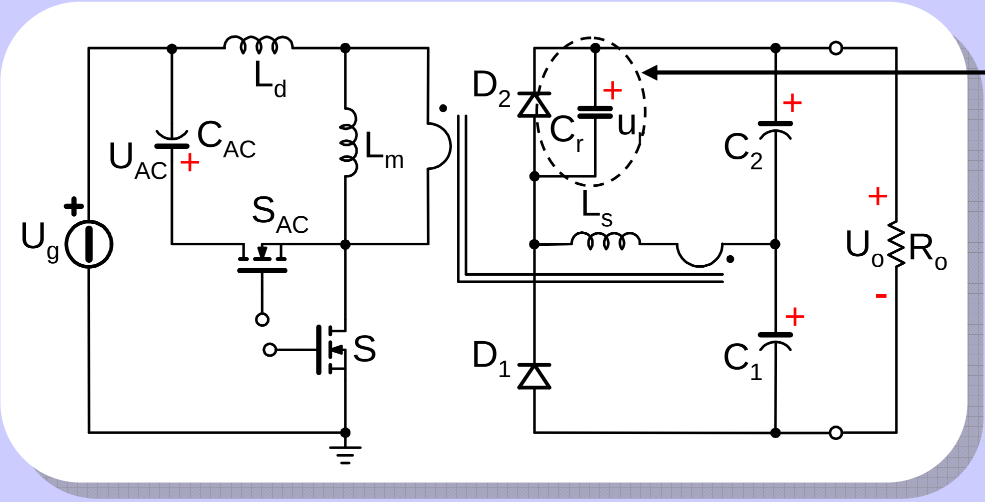
U_g = 35 V, U_o = 400 V, P_o = 300 W (2μs/div)



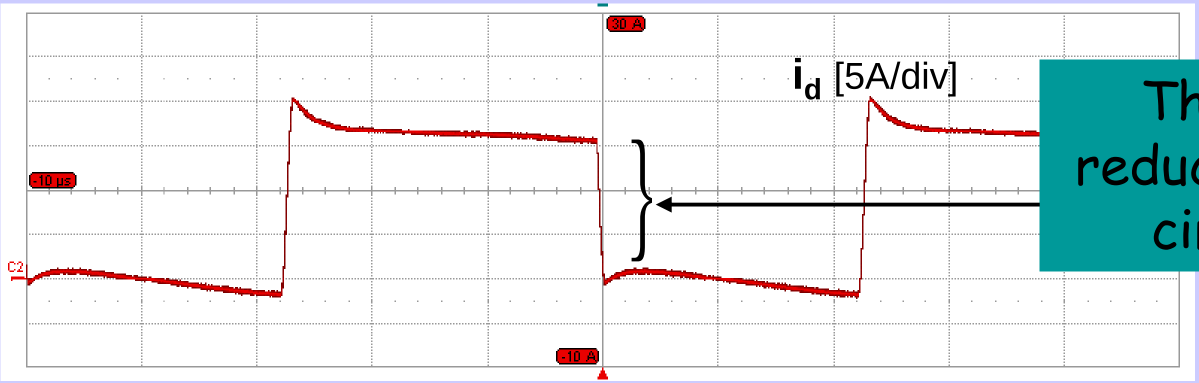
The resonant phase reduces the active clamp circulating current

Experimental Results

U_g = 35 V, U_o = 400 V, P_o = 300 W (2μs/div)



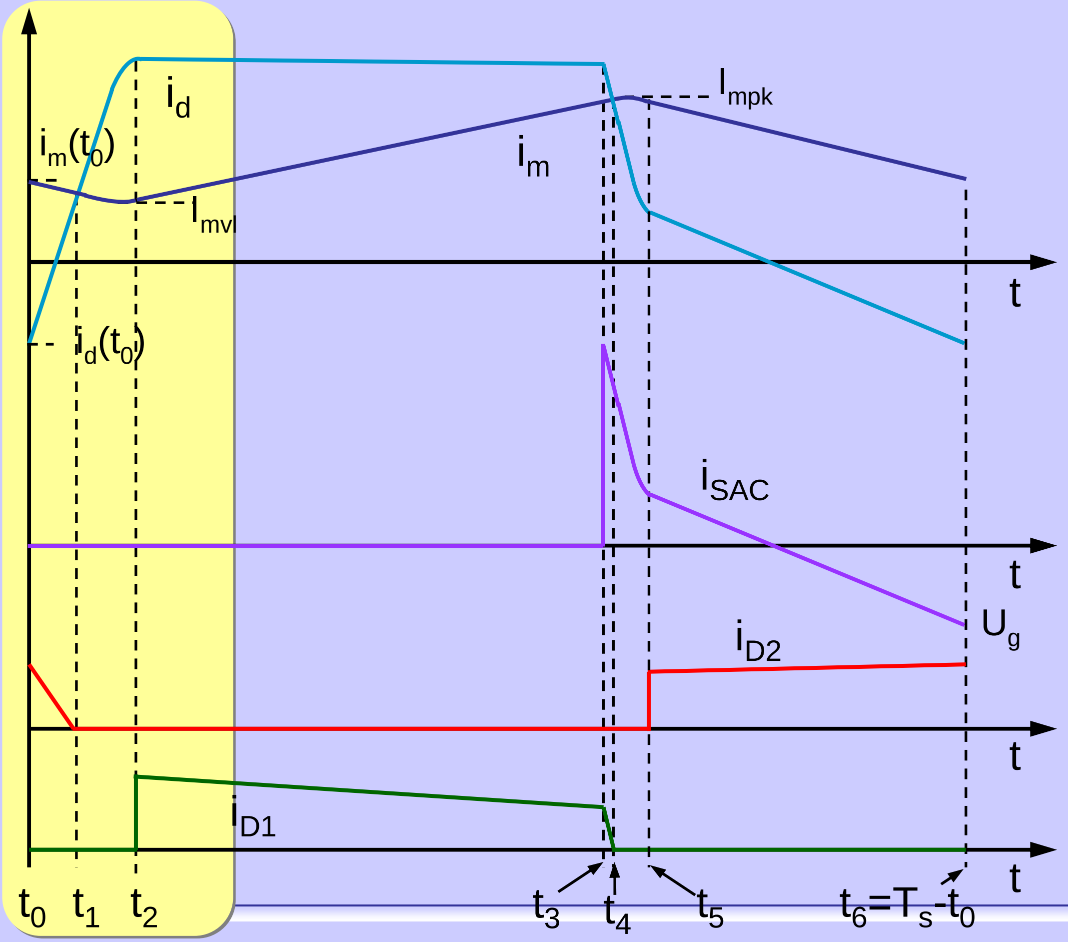
390 pF external capacitor added



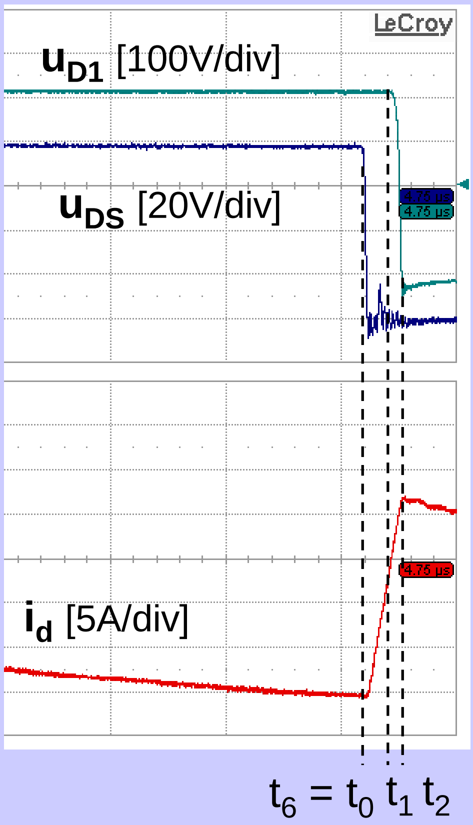
The resonant phase reduces the active clamp circulating current

Detail of Main Switch Turn On

U_g = 35 V, U_o = 400 V,
P_o = 300 W

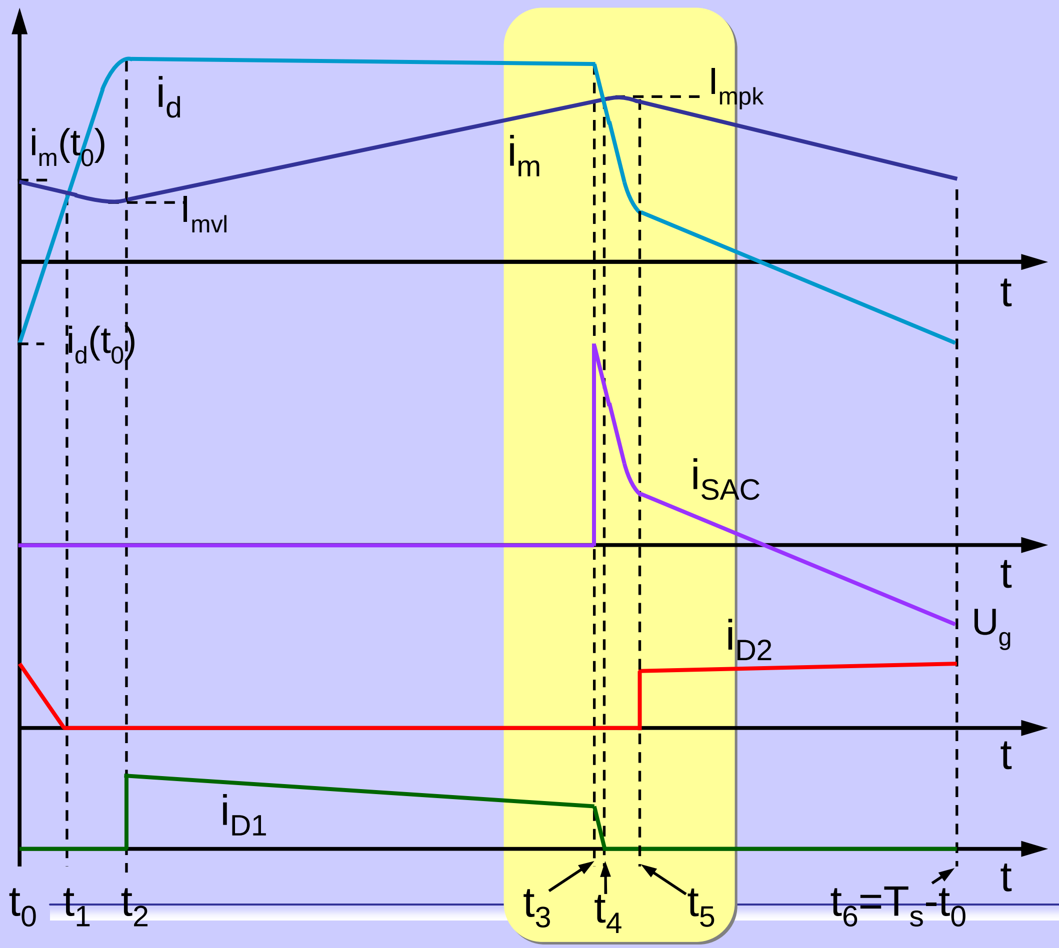


Time scale: 500ns/div

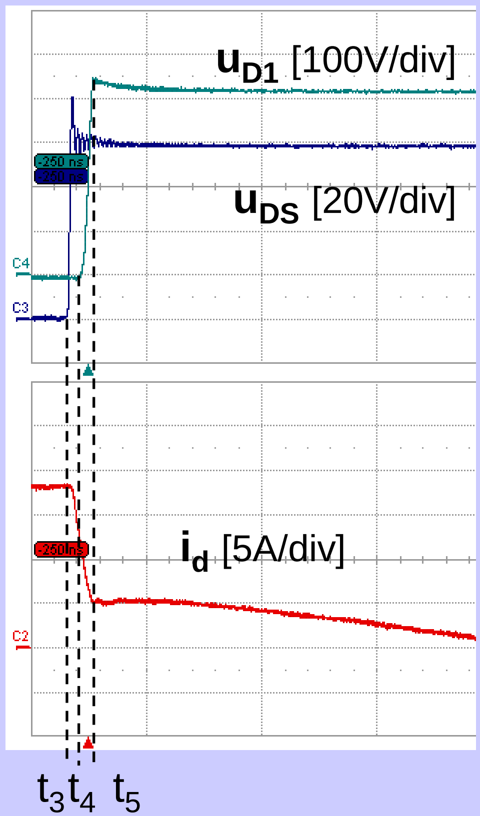


Detail of Main Switch Turn Off

U_g = 35 V, U_o = 400 V,
P_o = 300 W

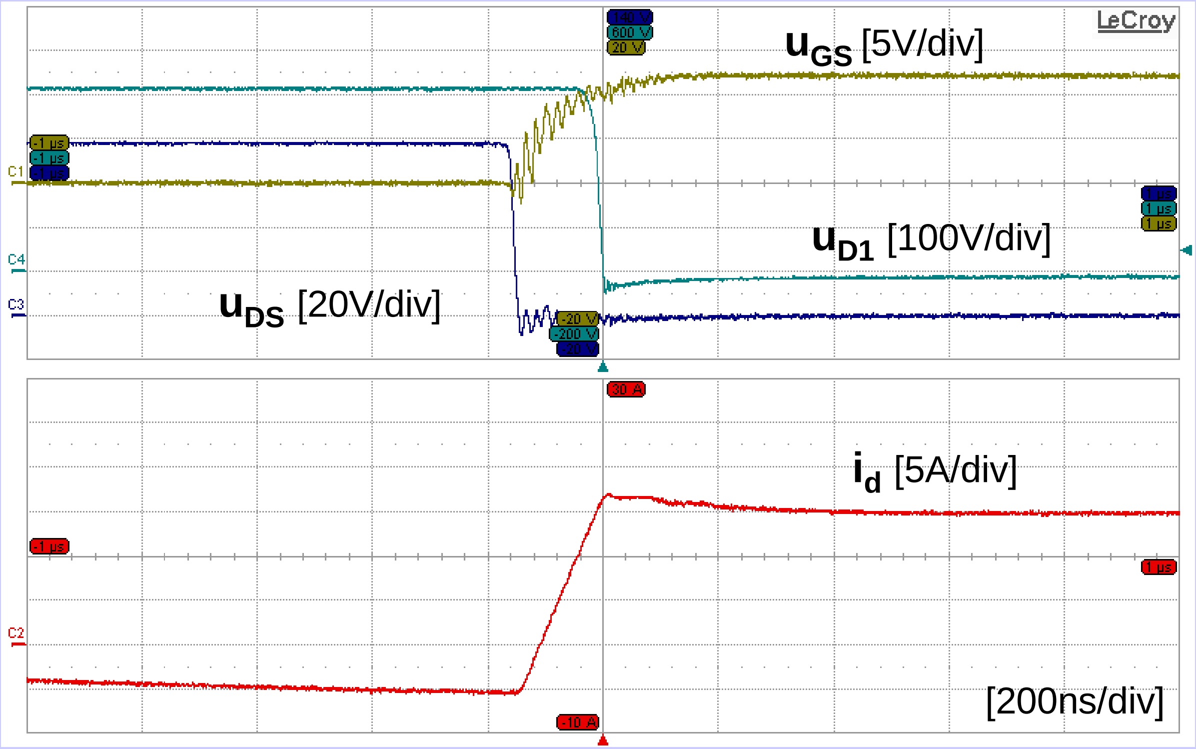


Time scale: 500ns/div



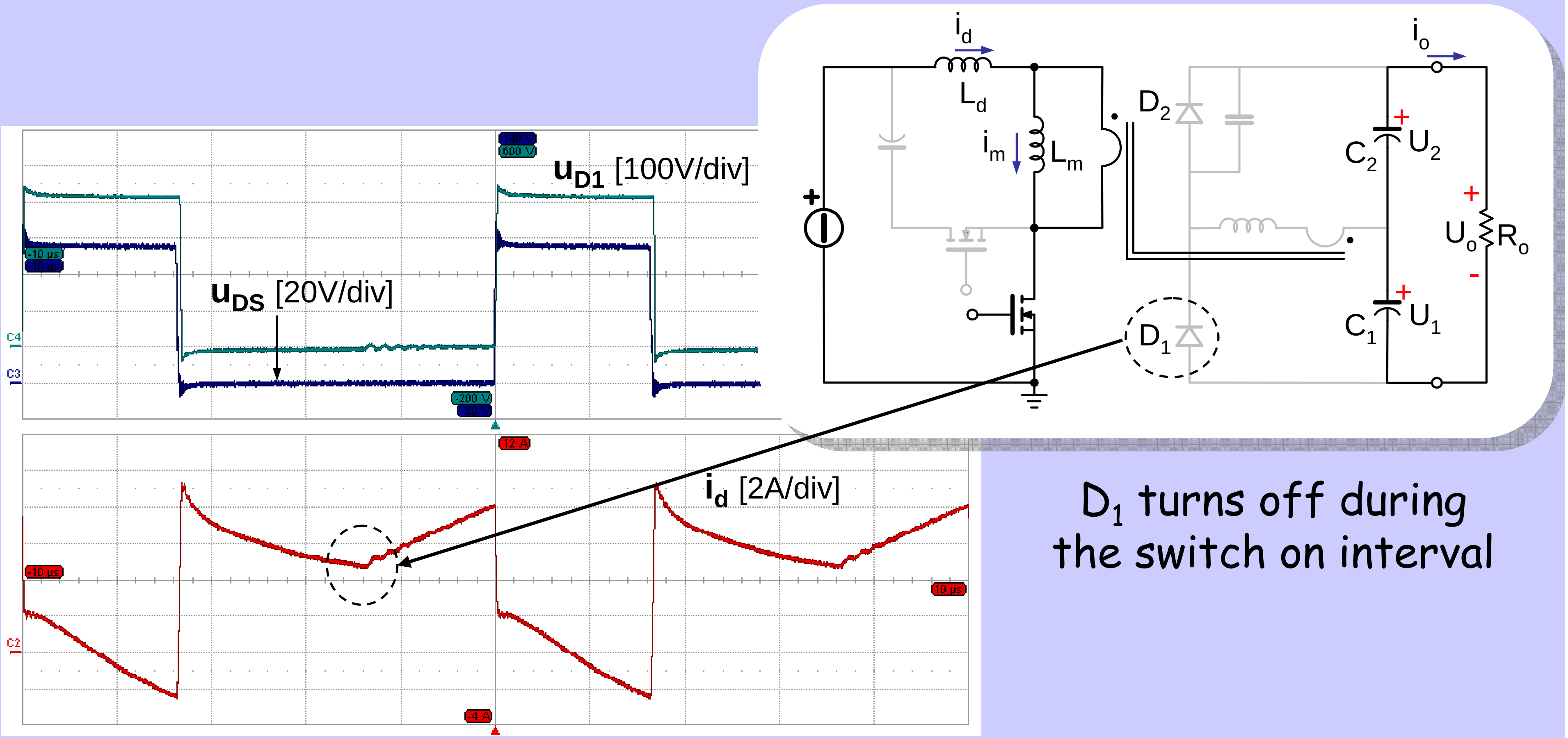
Zero Voltage Switching

Detail of the main switch turn on
(nominal output power)



Different Operating Mode

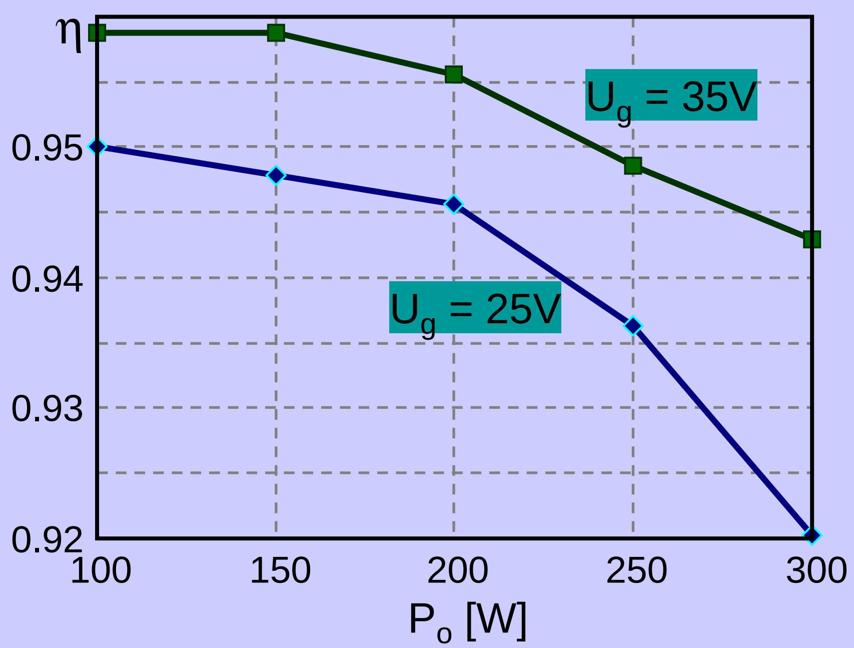
U_g = 25 V, U_o = 400 V, P_o = 100 W



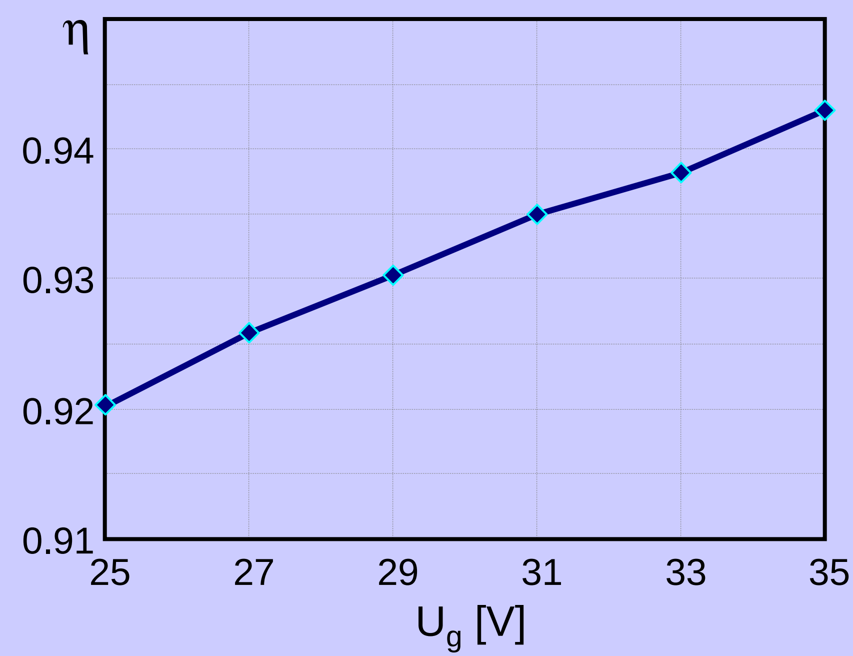
D_1 turns off during the switch on interval

Measured Efficiency

Power stage only



P_o = 300 W



Comments

- There are different topologies presented in literature whose behavior is very similar to the Integrated Boost-Flyback converter.
- These topologies have a drawback of a discontinuous input current waveform, that make the use of such converters for higher power levels at least problematic.
- For high power applications, a continuous input current represents a very nice feature