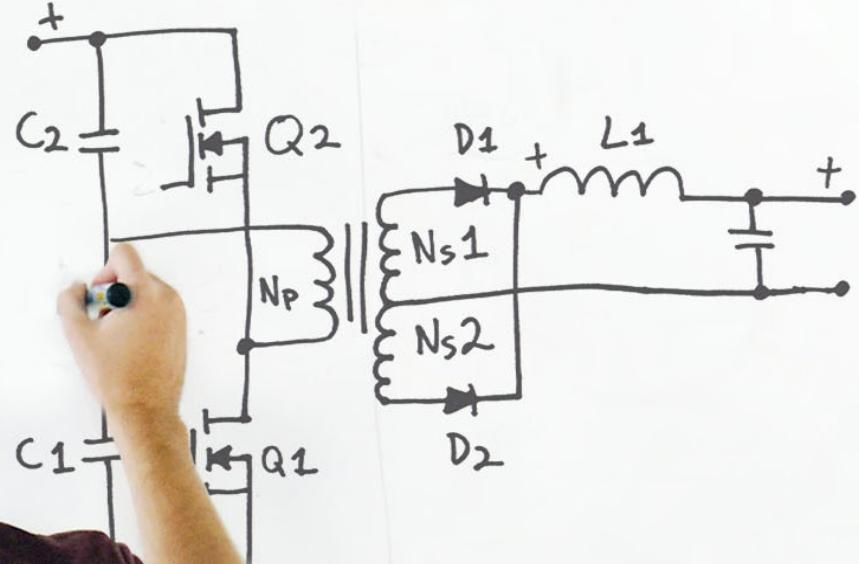


# Power Topologies Handbook



Half - Bridge



$$= \frac{V_{OUT} + V_F}{V_{IN} + V_F}$$

$$\sqrt{\frac{V_{OUT} + V_F}{V_{IN} \times \frac{N_p}{N_s}}}$$

This book shows waveforms and equations of the most common hard switched power supply topologies and the soft switched Phase-Shifted Full-Bridge. All equations are ideal with the only exception, that the forward voltage of rectifier and freewheeling diodes is taken into account. All those equations are also used in Texas Instruments's Power Stage Designer Tool, which can be found on the TI website under:  
[www.ti.com/tool/powerstage-designer](http://www.ti.com/tool/powerstage-designer)

# Power Topologies Handbook

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# Abbreviations and General Information

Expression	Abbreviation
Continuous Conduction Mode	CCM
Discontinuous Conduction Mode	DCM
Alternating Current	AC
Root Mean Square	RMS
Synchronous Rectifier	SR
Right Half Plane Zero	RHPZ
Input Voltage	$V_{in}$
Output Voltage	$V_{out}$
Output Current	$I_{out}$
Diode Forward Voltage	$V_f$
Switching frequency of the power supply's FET	$f_{switch}$
Switching period	$T_{switch} = \frac{1}{f_{switch}} = t_1 + t_2 + t_3$
Time, when the FET is conducting and current in the inductor is increasing.	$t_1$
Time, when the FET is not conducting and current in the inductor is decreasing.	$t_2$
Time, when the FET is not conducting and constant current or no current flows through the inductor for non-interleaved switching topologies. For interleaved switching topologies (e.g. Push-Pull) the current will decrease to 0A during that time.	$t_3$
Phase Shift Time	$t_{ph}$
Demagnetization Time	$t_d$
Time after demagnetization. Time period between $t_d$ and $t_1$ in DCM. Only applies for Single Switch Forward and Two Switch Forward.	$t_{ad}$
Duty Cycle	$D = t_1 \cdot f_{switch}$

## About Discontinuous Conduction Mode

A switch mode power supply enters Discontinuous Conduction Mode when half the inductor current ripple exceeds the average inductor current. Respectively the relative inductor current ripple will have a value of 200% or greater in DCM and the current will have a minimum value of 0A during  $t_3$ . An exception is the synchronous Buck converter without diode emulation, where the inductor current can also become negative, because it remains in CCM under conditions a non-synchronous Buck regulator enters DCM. In case of the SEPIC, Cuk and Zeta topologies the before mentioned conditions for DCM are a little bit different as those topologies contain two inductors. The inductor currents both have an offset in relationship to the input and output current. DCM is entered when both offsets have the same absolute value and sum up to zero. The relative inductor current ripple in DCM is also 200% or greater for SEPIC, Cuk and Zeta converters and the current during  $t_3$  will equal the value of the offset.

## About Inductors and Transformers

Coupling between coupled inductors and for transformer windings is assumed to be ideal. The equations for SEPIC, Cuk and Zeta converters are for uncoupled inductors: When calculating with coupled inductors for those topologies use double the value of the component's inductance. This also means that for the same ripple requirement a coupled inductor with half the inductance of a single inductor solution is sufficient. Another benefit of using coupled inductors for Cuk, SEPIC and Zeta is that the resonant frequency between inductors and coupling capacitor does not have an effect on the power supply's frequency response, but does with single inductors.

## About Diodes

The forward voltage drop of rectifier and freewheeling diodes ( $D_1$  and  $D_2$ , as well as  $D_3$  for the Weinberg) is taken into account for all calculations. It is assumed that the forward voltage drop is identical for those. The forward voltage drop for demagnetization diodes ( $D_3$  and  $D_4$ ) is neglected for all equations.

## About How waveforms are being displayed

The voltage and current waveforms of components are displayed in the direction the current is flowing through them. Exceptions are the secondaries of transformers and coupled inductors, because they are considered to be current sources. This results in the signs of current and voltage being inverse. For Inverting Buck-Boost and Cuk output voltage and current have to be negative values for calculations. The direction of voltage and current waveforms for the synchronous rectifier in the synchronous Buck regulator point to the opposite direction compared to the diode in the non-synchronous Buck regulator, because the voltage is measured from Drain to Source in this special case.

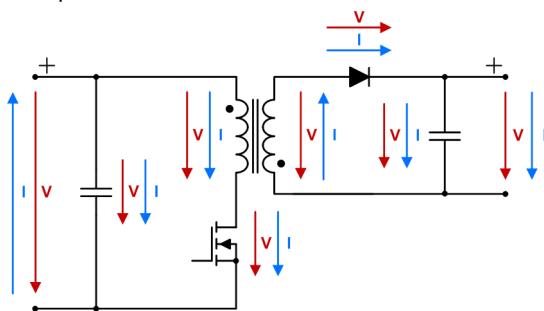


Figure 1.0.1.Example of how the waveforms of a Flyback converter are displayed.

## About Right Half Plane Zero

For Boost, Inverting Buck-Boost, Cuk, SEPIC, Flyback and Two Switch Flyback topologies the equations for the right half plane zero are very simplified and thus give the designer only an estimation of the frequency. Please consider that SEPIC and Cuk converters have more than one RHPZ and only one of them can be calculated to a certain extent.



# General Equations for Calculating RMS and AC Currents

## 2.1. Positive triangular waveforms without offset

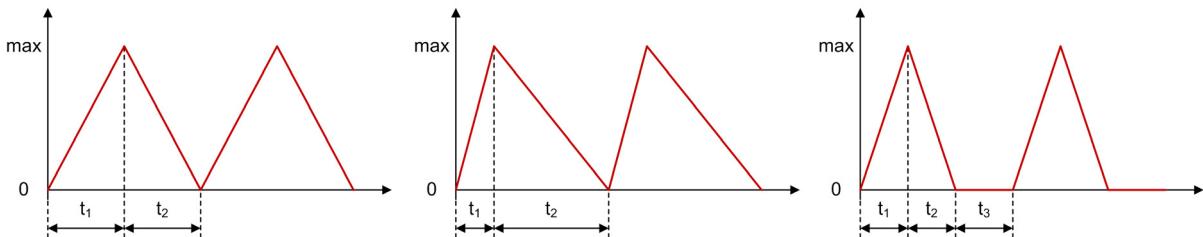


Figure 2.1.1. Positive triangular waveforms without offset

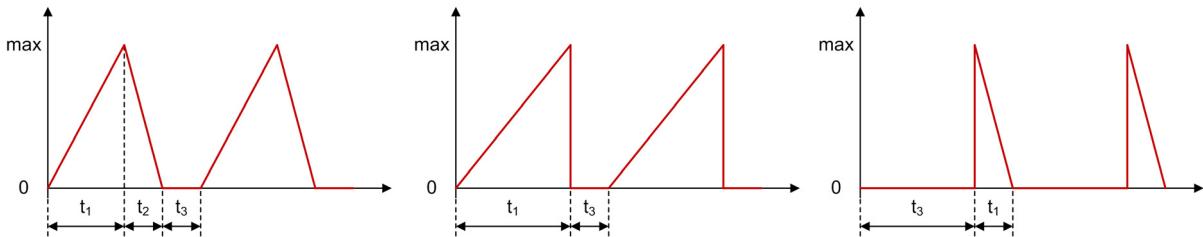


Figure 2.1.2. Positive triangular waveforms without offset

Average:

$$\text{avg} = \frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} i(t) \cdot dt$$

$$\text{avg} = \frac{\text{max}}{2} \cdot \frac{t_1+t_2}{T_{\text{switch}}}$$

RMS:

$$\text{rms} = \sqrt{\frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} (i(t))^2 \cdot dt}$$

$$\text{rms} = \text{max} \cdot \sqrt{\frac{t_1+t_2}{3 \cdot T_{\text{switch}}}}$$

AC:

$$\text{ac} = \sqrt{\text{rms}^2 - \text{avg}^2}$$

## 2.2. Positive triangular waveforms with offset

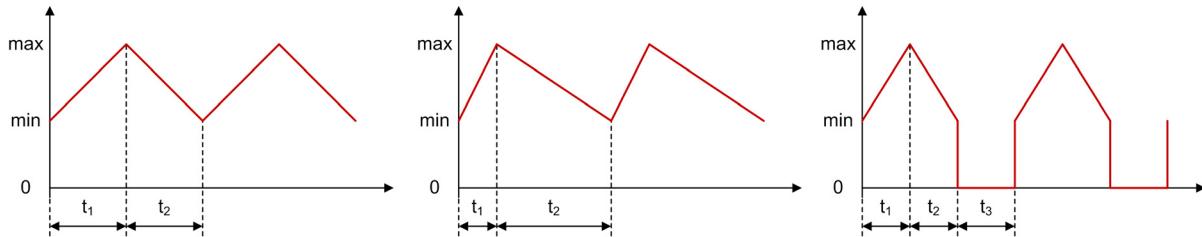


Figure 2.2.1. Positive triangular waveforms with offset

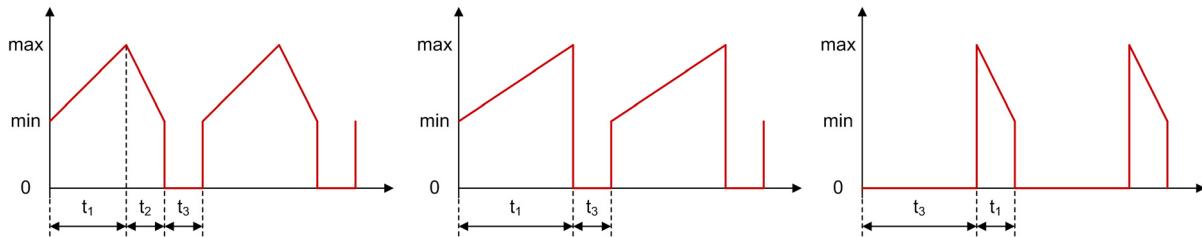


Figure 2.2.2. Positive triangular waveforms with offset

Average:

$$\text{avg} = \frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} i(t) \cdot dt$$

$$\text{avg} = \frac{\text{min} + \text{max}}{2} \cdot \frac{t_1 + t_2}{T_{\text{switch}}}$$

RMS:

$$\text{rms} = \sqrt{\frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} (i(t))^2 \cdot dt}$$

$$\text{rms} = \sqrt{\frac{t_1 + t_2}{T_{\text{switch}}} \cdot (\text{min} \cdot \text{max} + \frac{(\text{max} - \text{min})^2}{3})}$$

AC:

$$\text{ac} = \sqrt{\text{rms}^2 - \text{avg}^2}$$

### 2.3. Positive and negative triangular waveforms without offset

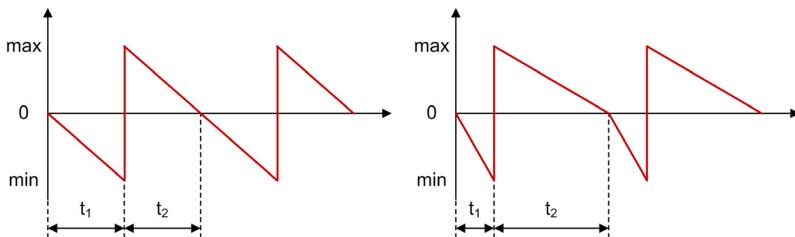


Figure 2.3.1. Positive and negative triangular waveforms without offset

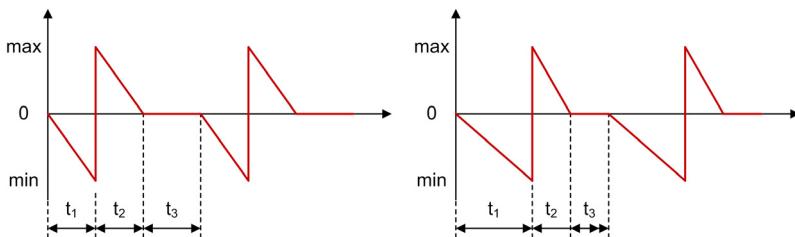


Figure 2.3.2. Positive and negative triangular waveforms without offset

Average:

$$\text{avg} = \frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} i(t) \cdot dt$$

$$\text{avg} = \frac{\min}{2} \cdot \frac{t_1}{T_{\text{switch}}} + \frac{\max}{2} \cdot \frac{t_2}{T_{\text{switch}}}$$

RMS:

$$\text{rms} = \sqrt{\frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} (i(t))^2 \cdot dt}$$

$$\text{rms} = \sqrt{\left(\min \cdot \sqrt{\frac{t_1}{3 \cdot T_{\text{switch}}}}\right)^2 + \left(\max \cdot \sqrt{\frac{t_2}{3 \cdot T_{\text{switch}}}}\right)^2}$$

AC:

$$\text{ac} = \sqrt{\text{rms}^2 - \text{avg}^2}$$

## 2.4. Positive and negative triangular waveforms with offset

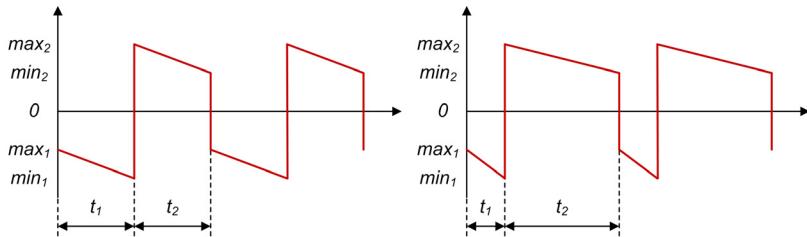


Figure 2.4.1. Positive and negative triangular waveforms with offset

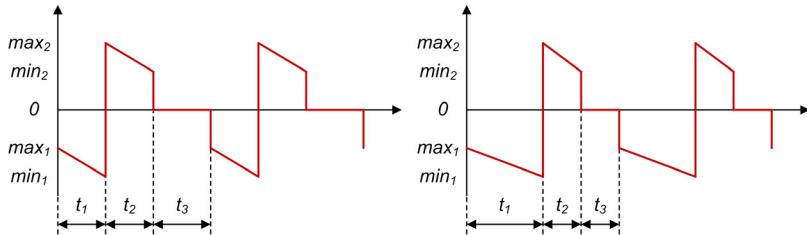


Figure 2.4.2. Positive and negative triangular waveforms with offset

Average:

$$\text{avg} = \frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} i(t) \cdot dt$$

$$\text{avg} = \frac{\min_1 + \max_1}{2} \cdot \frac{t_1}{T_{\text{switch}}} + \frac{\min_1 + \max_2}{2} \cdot \frac{t_2}{T_{\text{switch}}}$$

RMS:

$$\text{rms} = \sqrt{\frac{1}{T_{\text{switch}}} \int_0^{T_{\text{switch}}} (i(t))^2 \cdot dt}$$

$$\text{rms} = \sqrt{\frac{t_1}{T_{\text{switch}}} \cdot [\max_1 \cdot \min_1 + \frac{(\max_1 - \min_1)^2}{3}] + \frac{t_2}{T_{\text{switch}}} \cdot [\max_2 \cdot \min_2 + \frac{(\max_2 - \min_2)^2}{3}]}$$

AC:

$$\text{ac} = \sqrt{\text{rms}^2 - \text{avg}^2}$$

## 2.5. Universal equations for positive and negative triangular waveforms with Offset and three time components

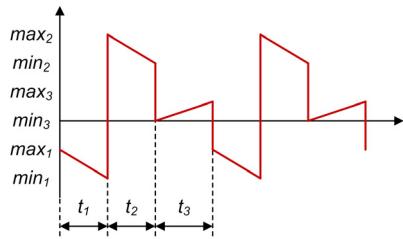


Figure 2.5.1. Positive and negative triangular waveforms with offset

Average:

$$avg = \frac{min_1+max_1}{2} \cdot \frac{t_1}{T_{switch}} + \frac{min_2+max_2}{2} \cdot \frac{t_2}{T_{switch}} + \frac{min_3+max_3}{2} \cdot \frac{t_3}{T_{switch}}$$

RMS:

$$rms = \sqrt{\sum_{n=1}^3 [f_{switch} \cdot t_n \cdot (max_n \cdot min_n + (max_n - min_n)^2)]}$$

AC:

$$ac = \sqrt{rms^2 - avg^2}$$

# Buck Converter

A Buck converter steps down an input voltage to a lower output voltage level. The energy is transferred to the output when the FET is conducting.

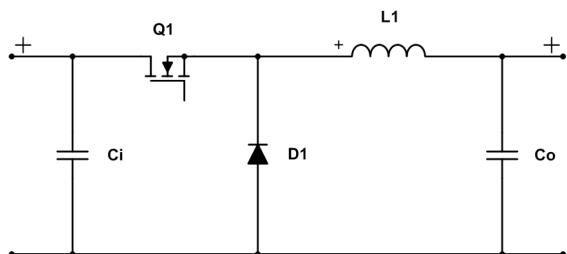


Figure 3.0.1. Schematic of a non-synchronous Buck converter

For calculating a synchronous Buck converter set  $V_f = 0V$ . The waveforms for the synchronous Buck converter show the operation in a forced PWM scenario, where a non-synchronous Buck converter would enter DCM. For normal operation there is an additional positive DC offset for the current of FET and Inductor. The CCM waveforms can be used as reference. In case of the synchronous rectifier current the additional DC offset is negative.

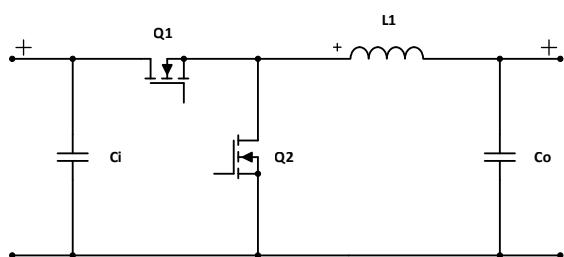


Figure 3.0.2. Schematic of a synchronous Buck converter

### 3.1. General

Inductor Current Ripple:  $I_{ripple} = \frac{1}{L_1} \cdot (V_{in} - V_{out}) \cdot t_1$

#### 3.1.1. Continuous Conduction Mode & Synchronous forced PWM.

$$\text{FET on, increasing current: } t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out}+V_f}{V_{in}+V_f}$$

$$\text{FET off, decreasing current: } t_2 = \frac{1}{f_{switch}} - t_1$$

$$\text{Min. Inductor Current: } I_{min} = I_{out} - \frac{I_{ripple}}{2}$$

$$\text{Max. Inductor Current: } I_{max} = I_{out} + \frac{I_{ripple}}{2}$$

$$\text{Average Input Current: } I_{in,avg} = \frac{V_{out} \cdot I_{out}}{V_{in}} + \frac{V_f}{V_{in}} \cdot \frac{I_{min}+I_{max}}{2} \cdot t_2 \cdot f_{switch}$$

#### 3.1.2. Discontinuous Conduction Mode.

$$\text{FET on, increasing current: } t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot (V_{in}-V_{out}) \cdot (V_{in}+V_f)}}$$

$$\text{FET off, decreasing current: } t_2 = t_1 \cdot \frac{V_{in}+V_f}{V_{out}+V_f} - t_1$$

$$\text{FET off, no current: } t_3 = \frac{1}{f_{switch}} - t_1 - t_2$$

$$\text{Min. Inductor Current: } I_{min} = 0A$$

$$\text{Max. Inductor Current: } I_{max} = \frac{1}{L_1} \cdot (V_{in} - V_{out}) \cdot t_1$$

$$\text{Average Input Current: } I_{in,avg} = \frac{V_{out} \cdot I_{out}}{V_{in}} + \frac{V_f}{V_{in}} \cdot \frac{I_{min}+I_{max}}{2} \cdot t_2 \cdot f_{switch}$$

### 3.2. Inductor $L_1$

#### 3.2.1. CCM, DCM & Synchronous forced PWM.

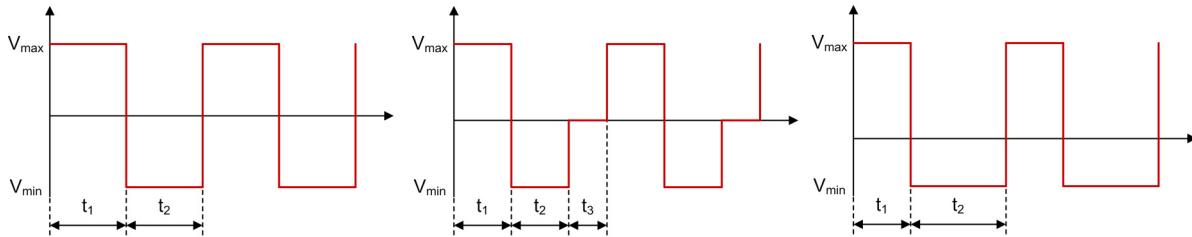
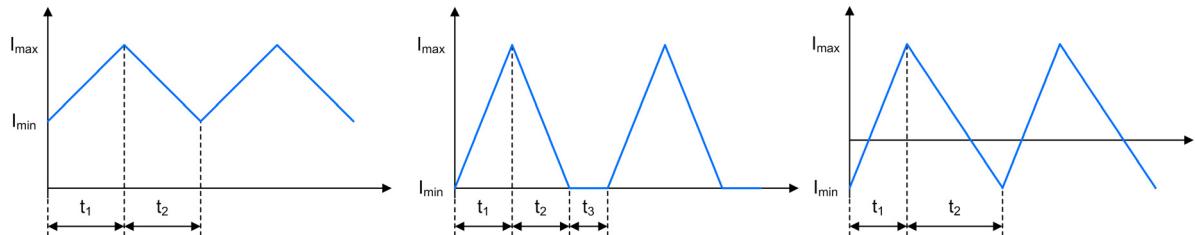


Figure 3.2.1. Buck - Inductor  $L_1$  Voltage Waveforms in CCM, DCM and synchronous forced PWM

Figure 3.2.2. Buck - Inductor  $L_1$  Current Waveforms in CCM, DCM and synchronous forced PWM

Average Inductor Current:  $I_{L1,avg} = \frac{I_{min} + I_{max}}{2} \cdot (t_1 + t_2) \cdot f_{switch}$

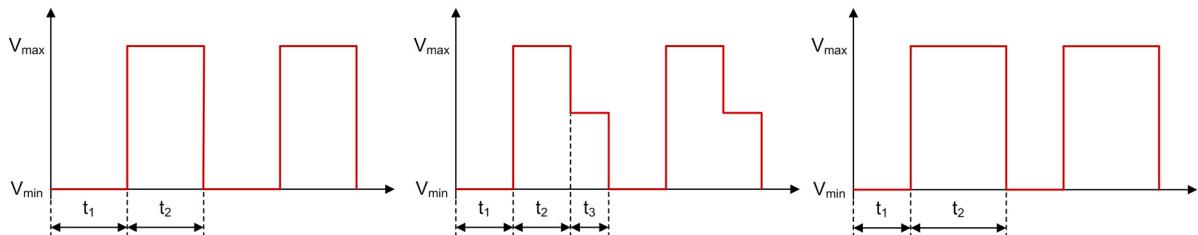
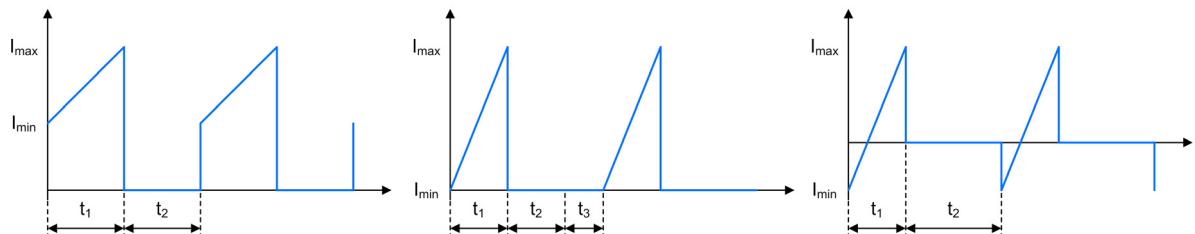
Min. Inductor Voltage:  $V_{L1,min} = -V_{out} - V_f$

Max. Inductor Voltage:  $V_{L1,max} = V_{in} - V_{out}$

Inductor Voltage during  $t_3$ :  $V_{L1,t_3} = 0V$

### 3.3. FET $Q_1$

#### 3.3.1. CCM, DCM & Synchronous forced PWM.

Figure 3.3.1. Buck - FET  $Q_1$  Voltage Waveforms in CCM, DCM and synchronous forced PWMFigure 3.3.2. Buck - FET  $Q_1$  Current Waveforms in CCM, DCM and synchronous forced PWM

Average FET Current:  $I_{Q_1,avg} = \frac{I_{min}+I_{max}}{2} \cdot t_1 \cdot f_{switch}$

Min. FET Voltage:  $V_{Q_1,min} = 0V$

Max. FET Voltage:  $V_{Q_1,max} = V_{in} + V_f$

FET Voltage during  $t_3$  (DCM):  $V_{Q_1,t_3} = V_{in} - V_{out}$

### 3.4. Diode $D_1$

#### 3.4.1. CCM & DCM.

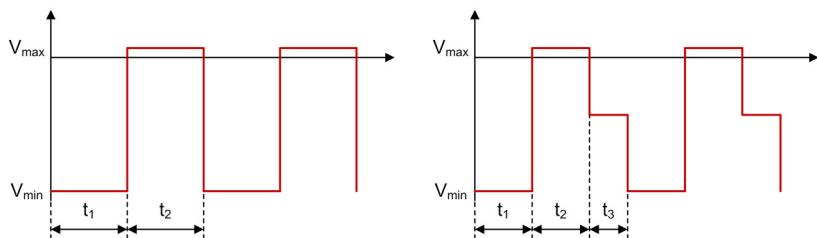


Figure 3.4.1. Buck - Diode  $D_1$  Voltage Waveforms in CCM and DCM

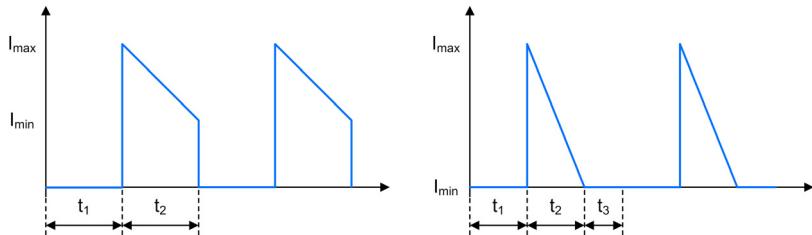


Figure 3.4.2. Buck - Diode  $D_1$  Current Waveforms in CCM and DCM

Average Diode Current:  $I_{D1,avg} = \frac{I_{min}+I_{max}}{2} \cdot t_2 \cdot f_{switch}$

Min. Diode Voltage:  $V_{D1,min} = -V_{in}$

Max. Diode Voltage:  $V_{D1,max} = V_f$

Diode Voltage during  $t_3$ :  $V_{D1,t_3} = -V_{out}$

### 3.4.2. Synchronous Rectifier FET $Q_2$ - forced PWM.

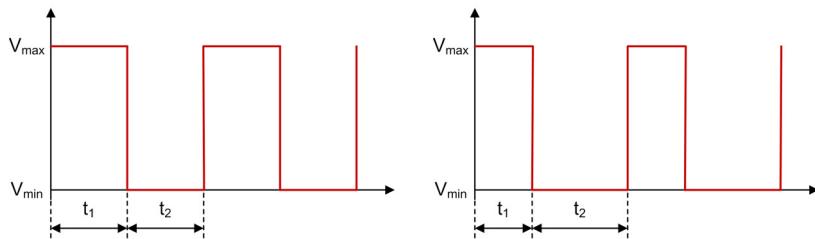


Figure 3.4.3. Synchronous Buck - Synchronous Rectifier FET  $Q_2$  Voltage Waveforms in CCM and forced PWM mode

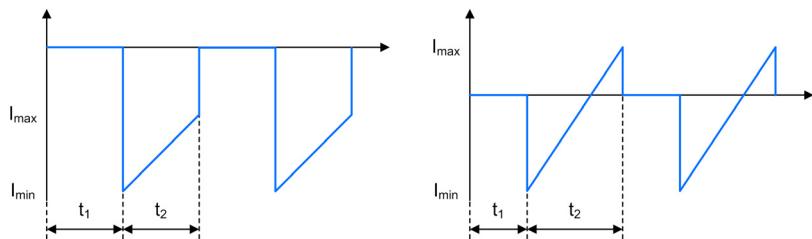


Figure 3.4.4. Synchronous Buck - Synchronous Rectifier FET  $Q_2$  Current Waveforms in CCM and forced PWM mode

Average SR Current:  $I_{Q_2,avg} = \frac{I_{min} + I_{max}}{2} \cdot t_2 \cdot f_{switch}$

Min. SR Voltage:  $V_{Q_2,min} = 0V$

Max. SR Voltage:  $V_{Q_2,max} = V_{in}$

### 3.5. Input Capacitor $C_i$

#### 3.5.1. CCM, DCM & Synchronous forced PWM.

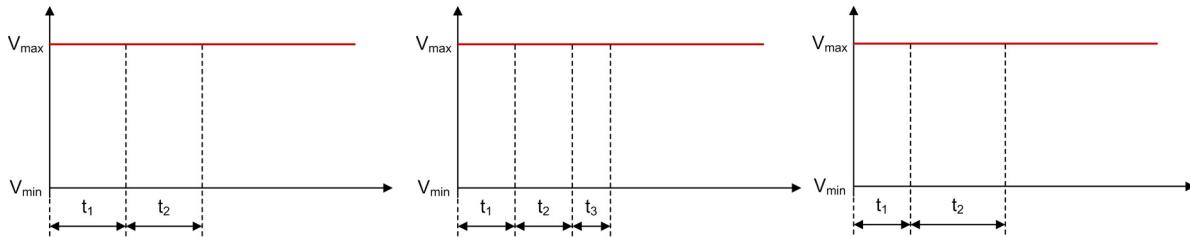


Figure 3.5.1. Buck - Input Capacitor  $C_i$  Voltage Waveforms in CCM, DCM and synchronous forced PWM

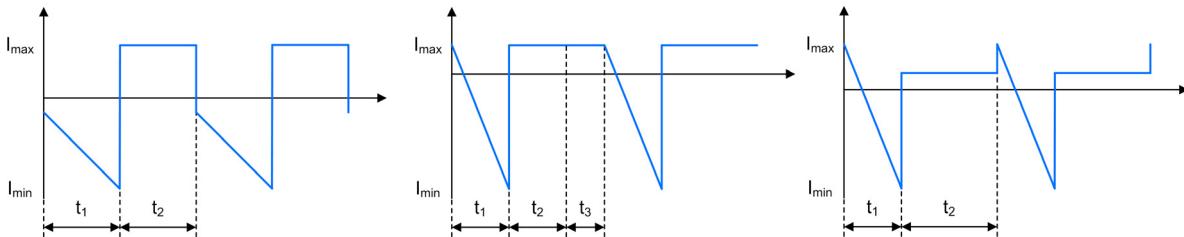


Figure 3.5.2. Buck - Input Capacitor  $C_i$  Current Waveforms in CCM, DCM and synchronous forced PWM

Min. Input Capacitor Current during  $t_1$ :  $I_{C_i,min,t_1} = -I_{max} + I_{in,avg}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_i,max,t_1} = -I_{min} + I_{in,avg}$

Input Capacitor Current during  $t_2$  and  $t_3$ :  $I_{C_i,t_{2/3}} = I_{in,avg}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

### 3.6. Output Capacitor $C_o$

#### 3.6.1. CCM, DCM & Synchronous forced PWM.

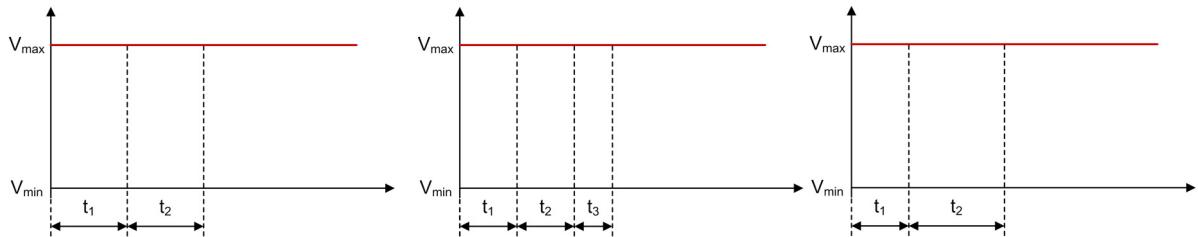


Figure 3.6.1. Buck - Output Capacitor  $C_o$  Voltage Waveforms in CCM, DCM and synchronous forced PWM

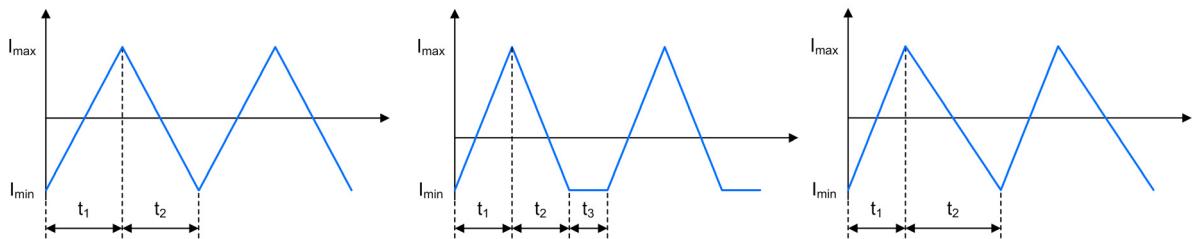


Figure 3.6.2. Buck - Output Capacitor  $C_o$  Current Waveforms in CCM, DCM and synchronous forced PWM

$$\text{Min. Output Capacitor Current: } I_{C_o,min} = I_{min} - I_{out}$$

$$\text{Max. Output Capacitor Current: } I_{C_o,max} = I_{max} - I_{out}$$

$$\text{Average Output Capacitor Current: } I_{C_o,avg} = 0A$$

$$\text{Output Capacitor Voltage: } V_{C_o} = V_{out}$$

# Boost Converter

A Boost converter steps up an input voltage to a higher output voltage level. The energy is transferred to the output when the FET is not conducting.

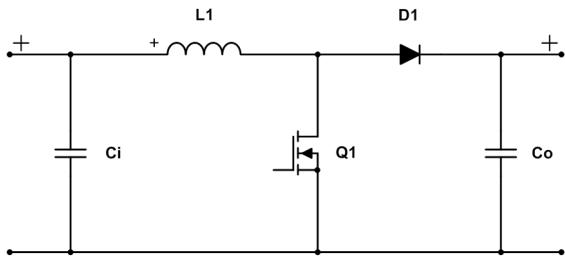


Figure 4.0.1. Schematic of a Boost converter

## 4.1. General

$$\text{Inductor Current Ripple: } I_{\text{ripple}} = \frac{1}{L_1} \cdot V_{\text{in}} \cdot t_1$$

$$\text{Right Half Plane Zero: } f_{\text{rhpz}} = \frac{V_{\text{out}} \cdot (1-D)^2}{2 \cdot \pi \cdot L_1 \cdot I_{\text{out}}}$$

### 4.1.1. CCM.

$$\text{FET on, increasing current: } t_1 = \frac{1}{f_{\text{switch}}} \cdot \frac{V_{\text{out}} + V_f - V_{\text{in}}}{V_{\text{out}} + V_f}$$

$$\text{FET off, decreasing current: } t_2 = \frac{1}{f_{\text{switch}}} - t_1$$

$$\text{Average Input Current: } I_{\text{in}} = I_{\text{out}} \cdot \frac{V_{\text{out}} + V_f}{V_{\text{in}}}$$

$$\text{Min. Inductor Current: } I_{\text{min}} = I_{\text{in}} - \frac{I_{\text{ripple}}}{2}$$

$$\text{Max. Inductor Current: } I_{\text{max}} = I_{\text{in}} + \frac{I_{\text{ripple}}}{2}$$

### 4.1.2. DCM.

$$\text{FET on, increasing current: } t_1 = \sqrt{2 \cdot I_{\text{out}} \cdot L_1 \cdot \frac{V_{\text{out}} + V_f - V_{\text{in}}}{f_{\text{switch}} \cdot V_{\text{in}}^2}}$$

$$\text{FET off, decreasing current: } t_2 = t_1 \cdot \frac{V_{\text{out}} + V_f}{V_{\text{out}} + V_f - V_{\text{in}}} - t_1$$

$$\text{FET off, no current: } t_3 = \frac{1}{f_{\text{switch}}} - t_1 - t_2$$

$$\text{Average Input Current: } I_{\text{in}} = I_{\text{out}} \cdot \frac{V_{\text{out}} \cdot V_f}{V_{\text{in}}}$$

$$\text{Min. Inductor Current: } I_{\text{min}} = 0A$$

$$\text{Max. Inductor Current: } I_{\text{max}} = \frac{1}{L_1} \cdot V_{\text{in}} \cdot t_1$$

## 4.2. Inductor $L_1$

### 4.2.1. CCM & DCM.

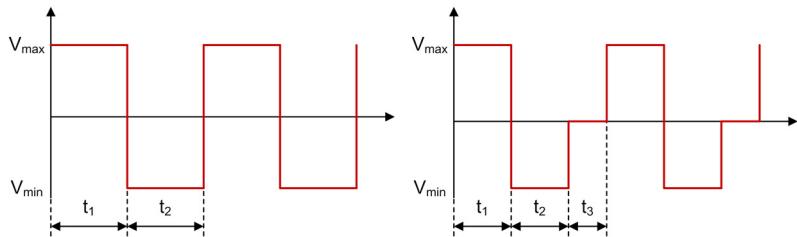


Figure 4.2.1. Boost - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

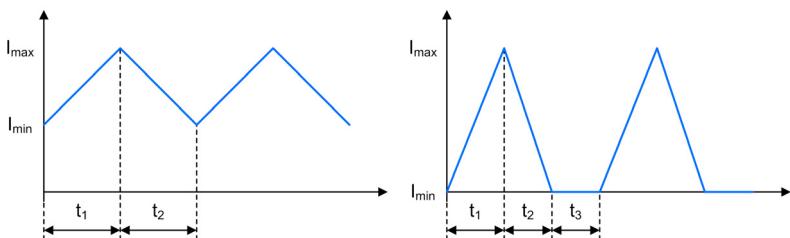


Figure 4.2.2. Boost - Inductor  $L_1$  Current Waveforms in CCM and DCM

$$\text{Average Inductor Current: } I_{L_1,\text{avg}} = \frac{I_{\text{min}} + I_{\text{max}}}{2} \cdot (t_1 + t_2) \cdot f_{\text{switch}}$$

$$\text{Min. Inductor Voltage: } V_{L_1,\text{min}} = V_{in} - V_{out} - V_f$$

$$\text{Max. Inductor Voltage: } V_{L_1,\text{max}} = V_{in}$$

$$\text{Inductor Voltage during } t_3: \quad V_{L_1,t_3} = 0V$$

### 4.3. FET $Q_1$

#### 4.3.1. CCM & DCM.

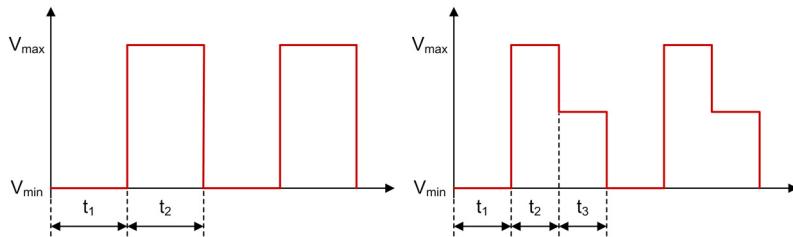


Figure 4.3.1. **Boost - FET  $Q_1$  Voltage Waveforms in CCM and DCM**

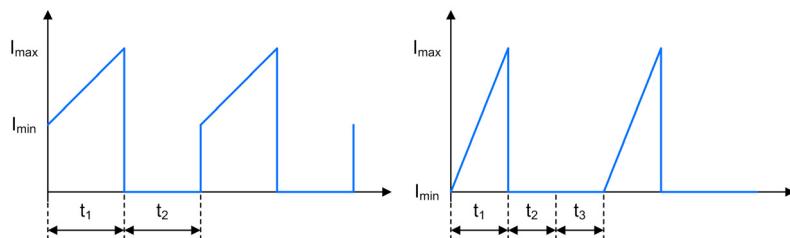


Figure 4.3.2. **Boost - FET  $Q_1$  Current Waveforms in CCM and DCM**

Average FET Current:  $I_{Q1,avg} = \frac{I_{min} + I_{max}}{2} \cdot t_1 \cdot f_{switch}$

Min. FET Voltage:  $V_{Q1,min} = 0V$

Max. FET Voltage:  $V_{Q1,max} = V_{out} + V_f$

FET Voltage during  $t_3$ :  $V_{Q1,t_3} = V_{in}$

## 4.4. Diode $D_1$

### 4.4.1. CCM & DCM.

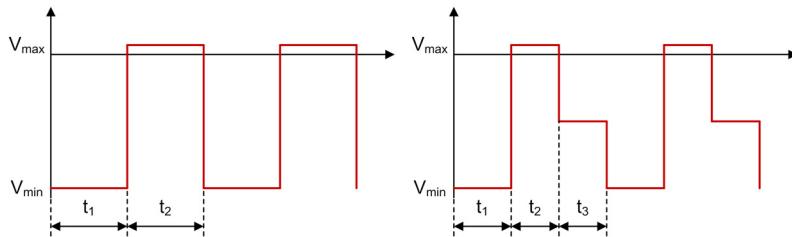


Figure 4.4.1. Boost - Diode  $D_1$  Voltage Waveforms in CCM and DCM

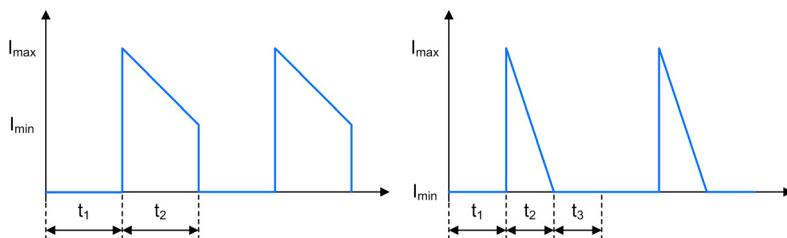


Figure 4.4.2. Boost - Diode  $D_1$  Current Waveforms in CCM and DCM

Average Diode Current:  $I_{D1,avg} = \frac{I_{min} + I_{max}}{2} \cdot t_2 \cdot f_{switch}$

Min. Diode Voltage:  $V_{D1,min} = -V_{out}$

Max. Diode Voltage:  $V_{D1,max} = V_f$

Diode Voltage during  $t_3$ :  $V_{D1,t_3} = V_{in} - V_{out}$

## 4.5. Input Capacitor $C_i$

### 4.5.1. CCM & DCM.

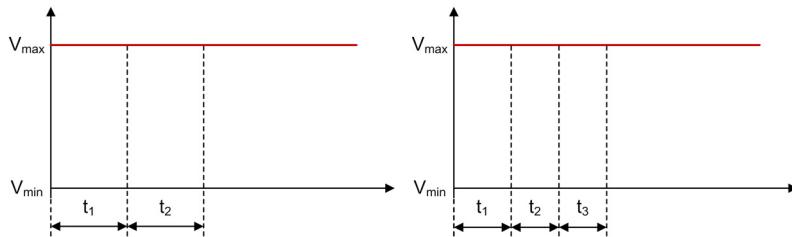


Figure 4.5.1. Boost - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

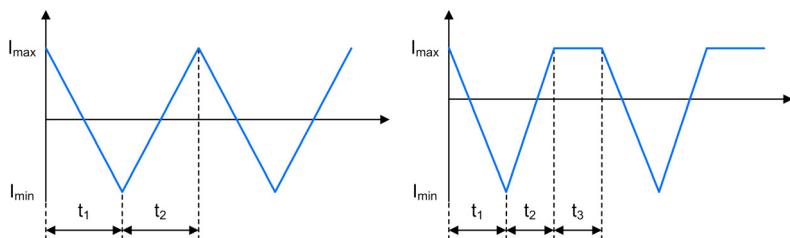


Figure 4.5.2. Boost - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current: } I_{C_i,min} = -I_{max} + I_{in}$$

$$\text{Max. Input Capacitor Current: } I_{C_i,max} = -I_{min} + I_{in}$$

$$\text{Average Input Capacitor Current: } I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage: } V_{C_i} = V_{in}$$

## 4.6. Output Capacitor $C_o$

### 4.6.1. CCM & DCM.

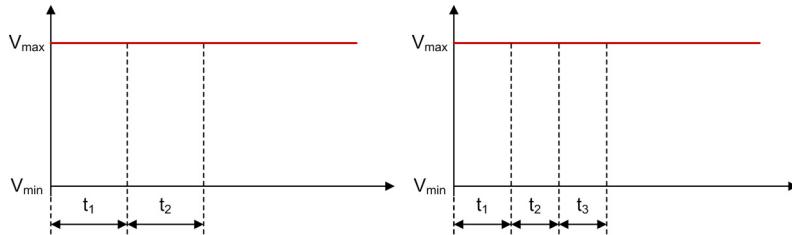


Figure 4.6.1. Boost - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

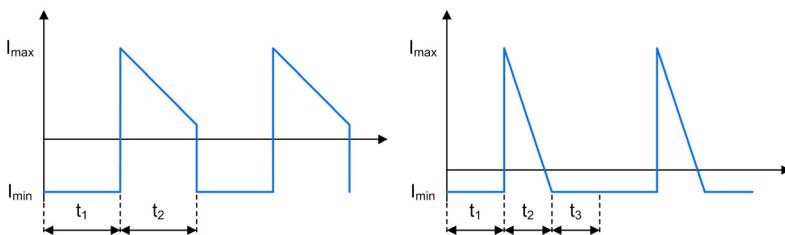


Figure 4.6.2. Boost - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Output Capacitor Current during  $t_1$ :

$$I_{C_o,t_1} = -I_{out}$$

Min. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,min,t_{2/3}} = I_{min} - I_{out}$$

Max. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,max,t_{2/3}} = I_{max} - I_{out}$$

Average Output Capacitor Current:

$$I_{C_o,avg} = 0A$$

Output Capacitor Voltage:

$$V_{C_o} = V_{out}$$



# Inverting Buck-Boost Converter

An Inverting Buck-Boost regulator converts a positive input voltage to a higher or lower negative output voltage level. The energy is transferred to the output when the FET is not conducting.

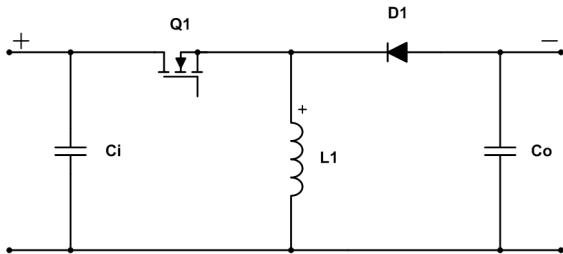


Figure 5.0.1. Schematic of an Inverting Buck-Boost converter

### 5.1. General

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot V_{in} \cdot t_1$$

$$\text{Right Half Plane Zero: } f_{rhpz} = \frac{V_{out} \cdot (1-D)^2}{2\pi \cdot D \cdot L_1 \cdot I_{out}}$$

#### 5.1.1. CCM.

$$\text{FET on, increasing current: } t_1 = \frac{1}{f_{switch}} \cdot \frac{-V_{out} + V_f}{-V_{out} + V_f + V_{in}}$$

$$\text{FET off, decreasing current: } t_2 = \frac{1}{f_{switch}} - t_1$$

$$\text{Min. Inductor Current: } I_{min} = -I_{out} \cdot \frac{V_{in} + V_f - V_{out}}{V_{in}} - \frac{I_{ripple}}{2}$$

$$\text{Max. Inductor Current: } I_{max} = -I_{out} \cdot \frac{V_{in} + V_f - V_{out}}{V_{in}} + \frac{I_{ripple}}{2}$$

$$\text{Average Input Current: } I_{in} = \frac{V_{out} \cdot I_{out}}{V_{in}} + \frac{V_f}{V_{in}} \cdot \frac{I_{min} + I_{max}}{2} \cdot t_2 \cdot f_{switch}$$

#### 5.1.2. DCM.

$$\text{FET on, increasing current: } t_1 = \sqrt{-2 \cdot I_{out} \cdot L_1 \cdot \frac{-V_{out} + V_f}{f_{switch} \cdot V_{in}^2}}$$

$$\text{FET off, decreasing current: } t_2 = t_1 \cdot \frac{-V_{out} + V_{in} + V_f}{-V_{out} + V_f} - t_1$$

$$\text{FET off, no current: } t_3 = \frac{1}{f_{switch}} - t_1 - t_2$$

$$\text{Min. Inductor Current: } I_{min} = 0A$$

$$\text{Max. Inductor Current: } I_{max} = \frac{1}{L_1} \cdot V_{in} \cdot t_1$$

$$\text{Average Input Current: } I_{in} = \frac{V_{out} \cdot I_{out}}{V_{in}} + \frac{V_f}{V_{in}} \cdot \frac{I_{max}}{2} \cdot t_2 \cdot f_{switch}$$

## 5.2. Inductor $L_1$

### 5.2.1. CCM & DCM.

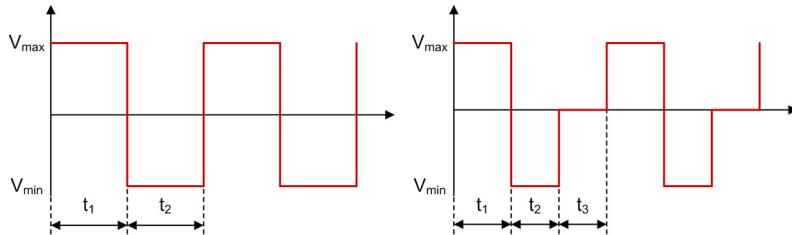


Figure 5.2.1. Inverting Buck Boost - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

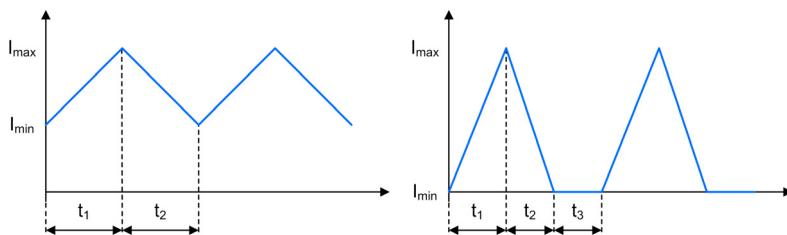


Figure 5.2.2. Inverting Buck Boost - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:  $I_{L_1,avg} = \frac{I_{min} + I_{max}}{2} \cdot (t_1 + t_2) \cdot f_{switch}$

Min. Inductor Voltage:  $V_{L_1,min} = V_{out} - V_f$

Max. Inductor Voltage:  $V_{L_1,max} = V_{in}$

Inductor Voltage during  $t_3$ :  $V_{L_1,t_3} = 0V$

### 5.3. FET $Q_1$

#### 5.3.1. CCM & DCM.

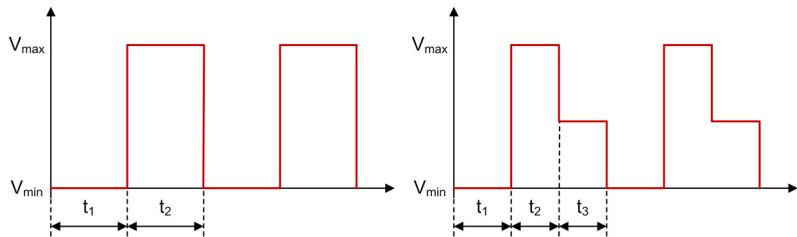


Figure 5.3.1. Inverting Buck Boost - FET  $Q_1$  Voltage Waveforms in CCM and DCM

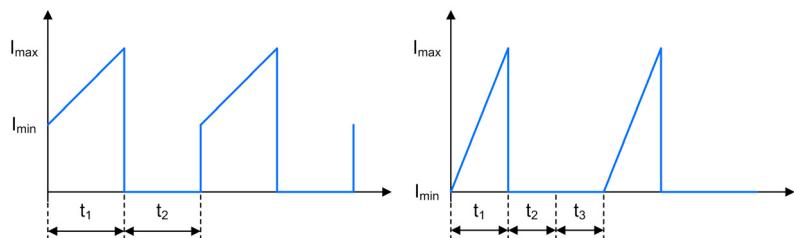


Figure 5.3.2. Inverting Buck Boost - FET  $Q_1$  Current Waveforms in CCM and DCM

Average FET Current:  $I_{Q_1,avg} = \frac{I_{min}+I_{max}}{2} \cdot t_1 \cdot f_{switch}$

Min. FET Voltage:  $V_{Q_1,min} = 0V$

Max. FET Voltage:  $V_{Q_1,max} = V_{in} + V_f - V_{out}$

FET Voltage during  $t_3$ :  $V_{Q_1,t_3} = V_{in}$

## 5.4. Diode $D_1$

### 5.4.1. CCM & DCM.

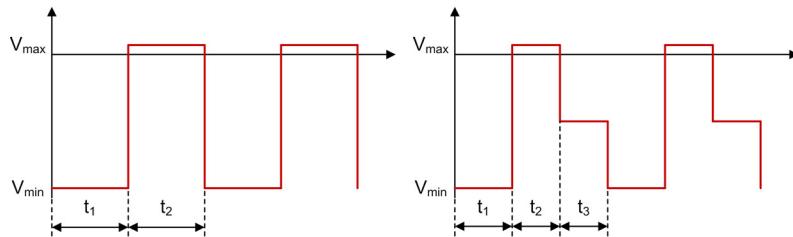


Figure 5.4.1. Inverting Buck Boost - Diode  $D_1$  Voltage Waveforms in CCM and DCM

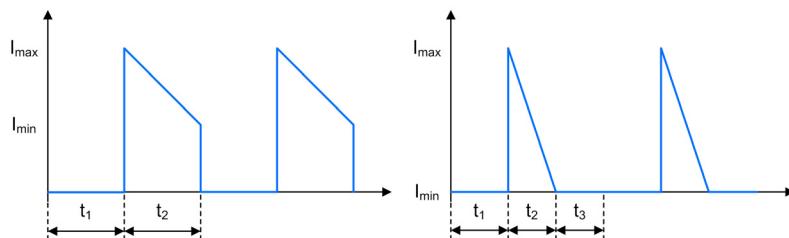


Figure 5.4.2. Inverting Buck Boost - Diode  $D_1$  Current Waveforms in CCM and DCM

$$\text{Average Diode Current: } I_{D_1,avg} = \frac{I_{min} + I_{max}}{2} \cdot t_2 \cdot f_{switch}$$

$$\text{Min. Diode Voltage: } V_{D_1,min} = V_{out} - V_{in}$$

$$\text{Max. Diode Voltage: } V_{D_1,max} = V_f$$

$$\text{Diode Voltage during } t_3: \quad V_{D_1,t_3} = V_{out}$$

### 5.5. Input Capacitor $C_i$

#### 5.5.1. CCM & DCM.

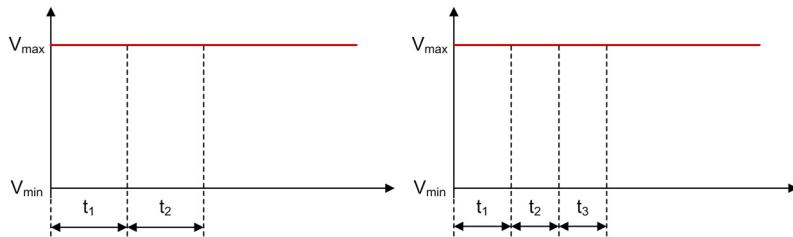


Figure 5.5.1. Inverting Buck Boost - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

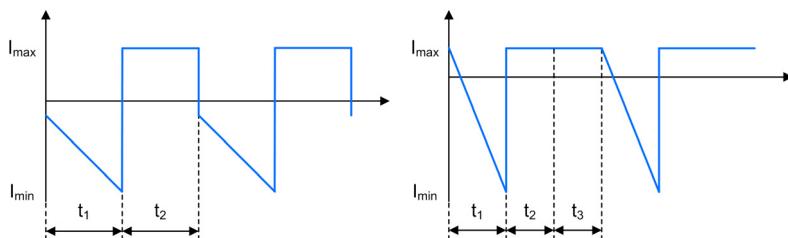


Figure 5.5.2. Inverting Buck Boost - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current during } t_1: \quad I_{C_i,min,t_1} = -I_{max} + I_{in}$$

$$\text{Max. Input Capacitor Current during } t_1: \quad I_{C_i,max,t_1} = -I_{min} + I_{in}$$

$$\text{Input Capacitor current during } t_2 \text{ and } t_3: \quad I_{C_i,t_{2/3}} = I_{in}$$

$$\text{Average Input Capacitor Current:} \quad I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage:} \quad V_{C_i} = V_{in}$$

## 5.6. Output Capacitor $C_o$

### 5.6.1. CCM & DCM.

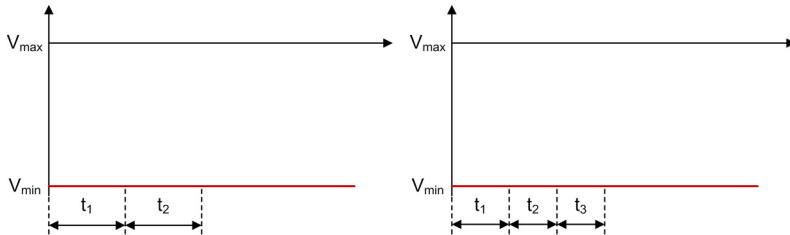


Figure 5.6.1. Inverting Buck Boost - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

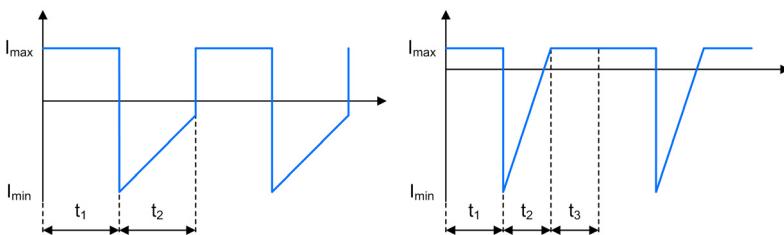


Figure 5.6.2. Inverting Buck Boost - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Output Capacitor Current during  $t_1$ :

$$I_{C_o,t_1} = -I_{out}$$

Min. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,min,t_{2/3}} = -I_{min} - I_{out}$$

Max. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,max,t_{2/3}} = -I_{max} - I_{out}$$

Average Output Capacitor Current:

$$I_{C_o,avg} = 0A$$

Output Capacitor Voltage:

$$V_{C_o} = V_{out}$$



## CHAPTER 6

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# SEPIC

A Single Ended Primary Inductor Converter (SEPIC) steps up/down an input voltage to a higher/lower output voltage level. The energy is transferred to the output when the FET is not conducting.

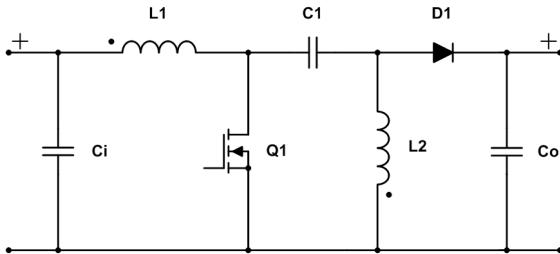


Figure 6.0.1. Schematic of a SEPIC converter

## 6.1. General

$$\text{Right Half Plane Zero: } f_{rhpz} = \frac{V_{out} \cdot (1-D)^2}{2 \cdot \pi \cdot D^2 \cdot L_1 \cdot I_{out}}$$

### 6.1.1. Continuous Conduction Mode.

FET on, increasing current:

$$t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out} + V_f}{V_{out} + V_{in} + V_f}$$

FET off, decreasing current:

$$t_2 = \frac{1}{f_{switch}} - t_1$$

Average Input Current:

$$I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$$

Inductor  $L_1$  Ripple:

$$I_{L_1,ripple} = V_{in} \cdot \frac{t_1}{L_1}$$

Inductor  $L_2$  Ripple:

$$I_{L_2,ripple} = V_{in} \cdot \frac{t_1}{L_2}$$

Coupling Capacitor  $C_1$  Voltage Ripple:

$$V_{C_1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$$

### 6.1.2. Discontinuous Conduction Mode.

FET on, increasing current:

$$t_1 = \frac{\sqrt{2 \cdot I_{out} \cdot L_1 \cdot L_2 \cdot (V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2)}}{V_{in} \cdot f_{switch} \cdot (L_1 + L_2)}$$

FET off, decreasing current:

$$t_2 = \frac{\sqrt{2 \cdot I_{out} \cdot L_1 \cdot L_2 \cdot (V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2)}}{(V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2)}$$

FET off, constant current:

$$t_3 = \frac{1}{f_{switch}} - t_1 - t_2$$

Average Input Current:

$$I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$$

Inductor  $L_1$  Ripple:

$$I_{L_1,ripple} = V_{in} \cdot \frac{t_1}{L_1}$$

Inductor  $L_2$  Ripple:

$$I_{L_2,ripple} = V_{in} \cdot \frac{t_1}{L_2}$$

Coupling Capacitor  $C_1$  Voltage Ripple:

$$V_{C_1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$$

## 6.2. Inductor $L_1$

### 6.2.1. CCM & DCM.

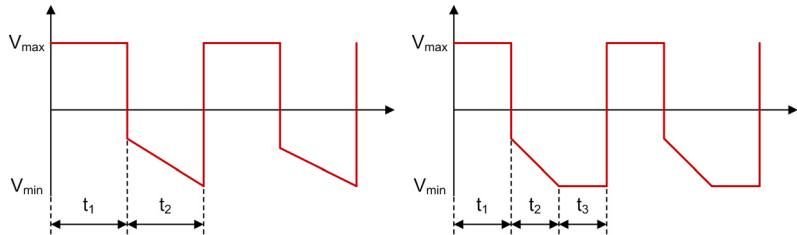


Figure 6.2.1. **SEPIC - Inductor  $L_1$  Voltage Waveforms in CCM and DCM**

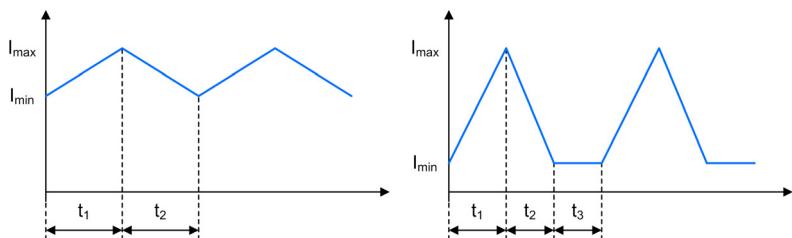


Figure 6.2.2. **SEPIC - Inductor  $L_1$  Current Waveforms in CCM and DCM**

Min. Inductor Current:  $I_{L1,min} = I_{in,avg} - \frac{1}{2} \cdot I_{L1,ripple} \cdot (t_1 + t_2) \cdot f_{switch}$

Max. Inductor Current:  $I_{L1,max} = I_{L1,min} + I_{L1,ripple}$

Average Inductor Current:  $I_{L1,avg} = I_{in,avg}$

Inductor Voltage during  $t_1$ :  $V_{L1,t_1} = V_{in}$

Min. Inductor Voltage during  $t_2$ :  $V_{L1,min,t_2} = -V_{out} - V_f - \frac{V_{C1,ripple}}{2}$

Max. Inductor Voltage during  $t_2$ :  $V_{L1,max,t_2} = -V_{out} - V_f + \frac{V_{C1,ripple}}{2}$

Inductor Voltage during  $t_3$ :  $V_{L1,t_3} = 0V$

The offset in DCM during  $t_3$  is dependent on the input voltage and can be positive or negative.

### 6.3. Inductor $L_2$

#### 6.3.1. CCM.

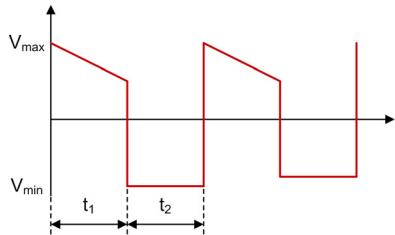


Figure 6.3.1. **SEPIC - Inductor  $L_2$  Voltage Waveform in CCM**

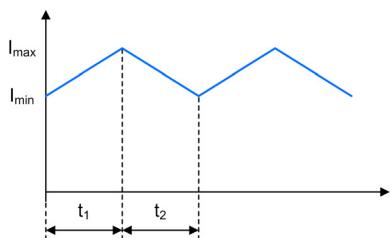


Figure 6.3.2. **SEPIC - Inductor  $L_2$  Current Waveform in CCM**

Min. Inductor Current:  $I_{L_2,min} = I_{out} - \frac{I_{L_2,ripple}}{2}$

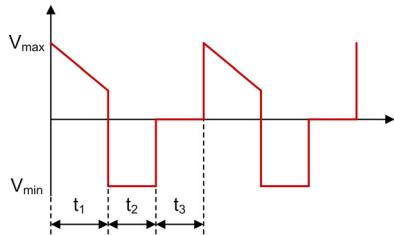
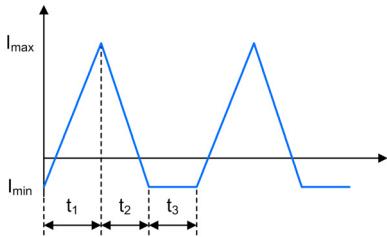
Max. Inductor Current:  $I_{L_2,max} = I_{L_2,min} + I_{L_2,ripple}$

Average Inductor Current:  $I_{L_2,avg} = I_{out}$

Min. Inductor Voltage during  $t_1$ :  $V_{L_2,min,t_1} = V_{in} - \frac{V_{C_1,ripple}}{2}$

Max. Inductor Voltage during  $t_1$ :  $V_{L_2,max,t_1} = V_{in} + \frac{V_{C_1,ripple}}{2}$

Inductor Voltage during  $t_2$ :  $V_{L_2,t_2} = -V_{out} - V_f$

**6.3.2. DCM.**Figure 6.3.3. SEPIC - Inductor  $L_2$  Voltage Waveform in DCMFigure 6.3.4. SEPIC - Inductor  $L_2$  Current Waveform in DCM

$$\text{Min. Inductor Current: } I_{L_2,\text{min}} = -I_{L_1,\text{min}}$$

$$\text{Max. Inductor Current: } I_{L_2,\text{max}} = I_{L_2,\text{min}} + I_{L_2,\text{ripple}}$$

$$\text{Average Inductor Current: } I_{L_2,\text{avg}} = I_{\text{out}}$$

$$\text{Min. Inductor Voltage during } t_1: \quad V_{L_2,\text{min},t_1} = V_{in} - \frac{V_{C_1,\text{ripple}}}{2}$$

$$\text{Max. Inductor Voltage during } t_1: \quad V_{L_2,\text{max},t_1} = V_{in} + \frac{V_{C_1,\text{ripple}}}{2}$$

$$\text{Inductor Voltage during } t_2: \quad V_{L_2,t_2} = -V_{out} - V_f$$

$$\text{Inductor Voltage during } t_3: \quad V_{L_2,t_3} = 0V$$

The offset in DCM during  $t_3$  is dependent on the input voltage and can be positive or negative.

## 6.4. FET $Q_1$

### 6.4.1. CCM & DCM.

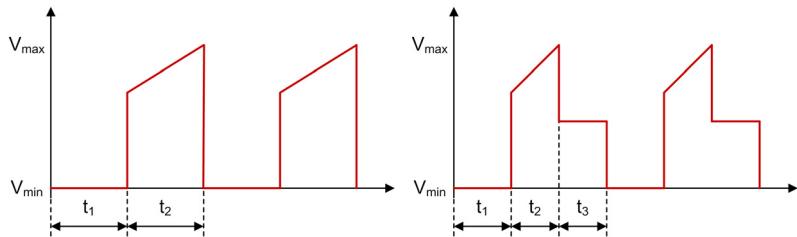


Figure 6.4.1. SEPIC - FET  $Q_1$  Voltage Waveforms in CCM and DCM

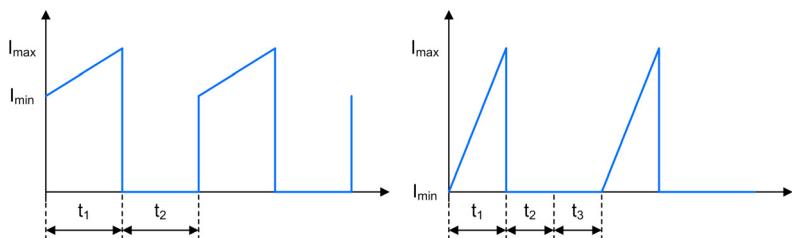


Figure 6.4.2. SEPIC - FET  $Q_1$  Current Waveforms in CCM and DCM

Min. FET Current:  $I_{Q_1,min} = I_{L_1,min} + I_{L_2,min}$

Max. FET Current:  $I_{Q_1,max} = I_{L_1,max} + I_{L_2,max}$

Average FET Current:  $I_{Q_1,avg} = I_{in,avg}$

FET Voltage during  $t_1$ :  $V_{Q_1,t_1} = 0V$

Min. FET Voltage during  $t_2$ :

$$V_{Q_1,min,t_2} = V_{in} + V_{out} + V_f - \frac{V_{C_1,ripple}}{2}$$

Max. FET Voltage during  $t_2$ :

$$V_{Q_1,max,t_2} = V_{in} + V_{out} + V_f + \frac{V_{C_1,ripple}}{2}$$

FET Voltage during  $t_3$ :

$$V_{Q_1,t_3} = V_{in}$$

## 6.5. Diode $D_1$

### 6.5.1. CCM & DCM.

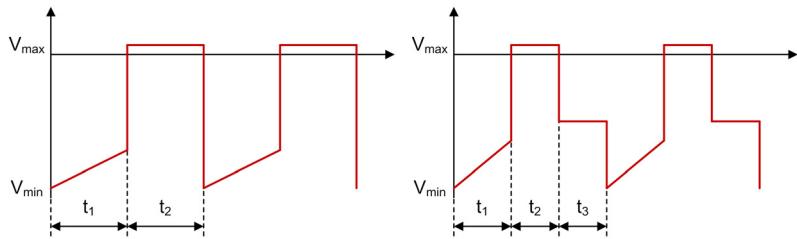


Figure 6.5.1. **SEPIC - Diode  $D_1$  Voltage Waveforms in CCM and DCM**

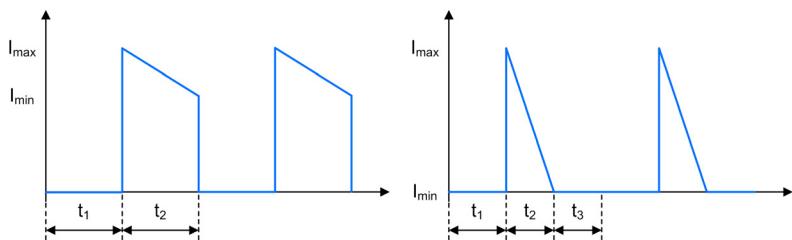


Figure 6.5.2. **SEPIC - Diode  $D_1$  Current Waveforms in CCM and DCM**

$$\text{Min. Diode Current: } I_{D1,min} = I_{L1,min} + I_{L2,min}$$

$$\text{Max. Diode Current: } I_{D1,max} = I_{L1,max} + I_{L2,max}$$

$$\text{Average Diode Current: } I_{D1,avg} = I_{out}$$

$$\text{Min. Diode Voltage during } t_1: \quad V_{D1,min,t_1} = -V_{in} - V_{out} - \frac{V_{C1,ripple}}{2}$$

$$\text{Max. Diode Voltage during } t_1: \quad V_{D1,max,t_1} = -V_{in} - V_{out} + \frac{V_{C1,ripple}}{2}$$

$$\text{Diode Voltage during } t_2: \quad V_{D1,t_2} = V_f$$

$$\text{Diode Voltage during } t_3: \quad V_{D1,t_3} = -V_{out}$$

## 6.6. Coupling Capacitor $C_1$

### 6.6.1. CCM & DCM.

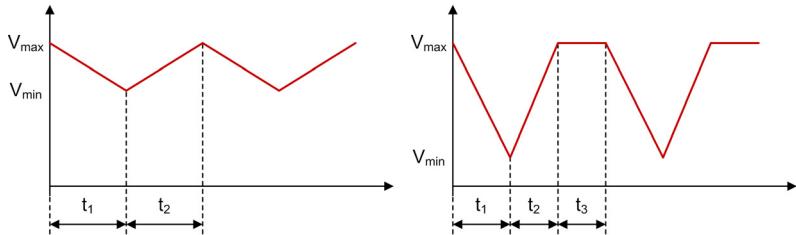


Figure 6.6.1. SEPIC - Coupling Capacitor  $C_1$  Voltage Waveforms in CCM and DCM

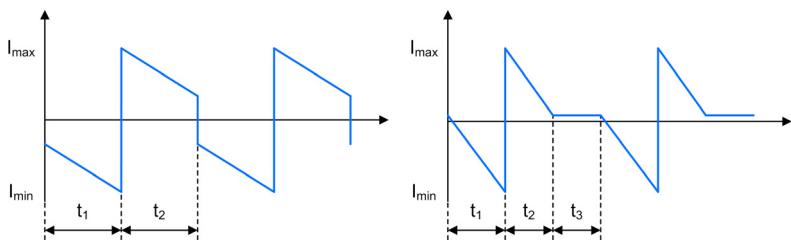


Figure 6.6.2. SEPIC - Coupling Capacitor  $C_1$  Current Waveforms in CCM and DCM

Min. Coupling Capacitor Current during  $t_1$ :  $I_{C_1,min,t_1} = I_{L_1,max} - I_{fet,max}$

Max. Coupling Capacitor Current during  $t_1$ :  $I_{C_1,max,t_1} = I_{L_1,min} - I_{fet,min}$

Min. Coupling Capacitor Current during  $t_2$ :  $I_{C_1,min,t_2} = I_{L_1,min}$

Max. Coupling Capacitor Current during  $t_2$ :  $I_{C_1,max,t_2} = I_{L_1,max}$

Coupling Capacitor Current during  $t_3$ :  $I_{C_1,t_3} = I_{L_1,min}$

Average Coupling Capacitor Current:  $I_{C_1,avg} = 0A$

Min. Coupling Capacitor Voltage:  $V_{C_1,min} = V_{in} - \frac{V_{C_1,ripple}}{2}$

Max. Coupling Capacitor Voltage:  $V_{C_1,max} = V_{in} + \frac{V_{C_1,ripple}}{2}$

Coupling Capacitor Voltage during  $t_3$ :  $V_{C_1,t_3} = V_{in}$

## 6.7. Input Capacitor $C_i$

### 6.7.1. CCM & DCM.

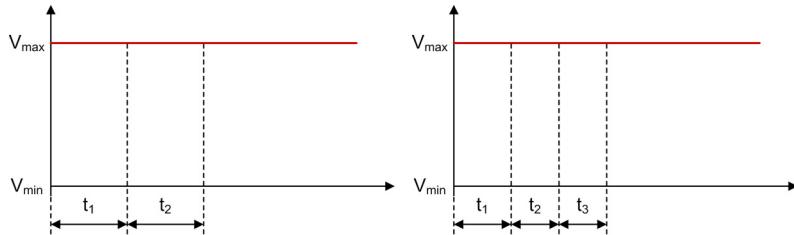


Figure 6.7.1. SEPIC - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

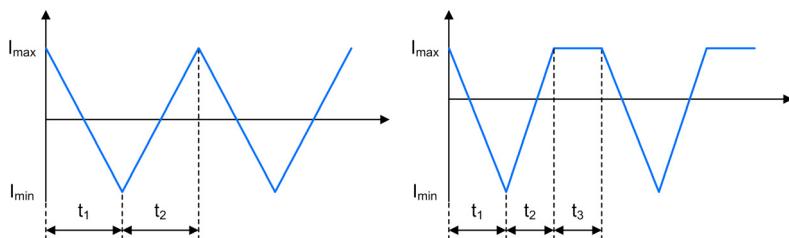


Figure 6.7.2. SEPIC - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

Min. Input Capacitor Current:  $I_{C_i,min} = I_{in,avg} - I_{L_1,max}$

Max. Input Capacitor Current:  $I_{C_i,max} = I_{in,avg} - I_{L_1,min}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

## 6.8. Output Capacitor $C_o$

### 6.8.1. CCM & DCM.

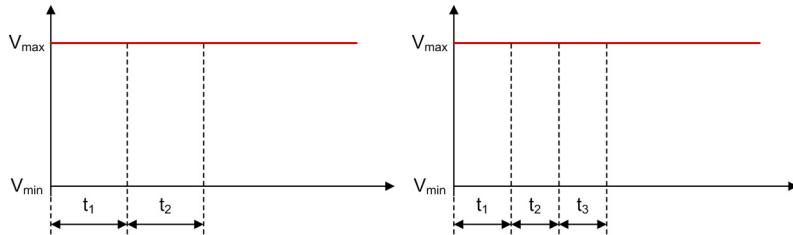


Figure 6.8.1. SEPIC - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

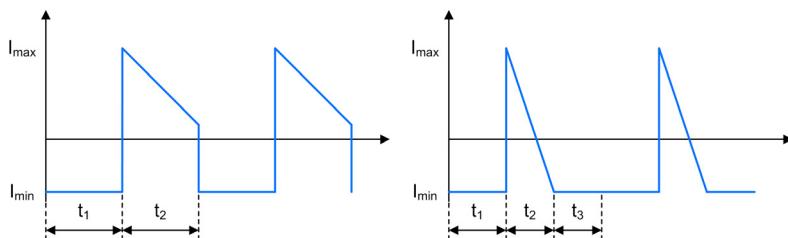


Figure 6.8.2. SEPIC - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Output Capacitor Current during  $t_1$ :

$$I_{C_o,t_1} = -I_{out}$$

Min. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,min,t_{2/3}} = I_{L1,min} + I_{L2,min} - I_{out}$$

Max. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,max,t_{2/3}} = I_{L1,max} + I_{L2,max} - I_{out}$$

Average Output Capacitor Current:

$$I_{C_o,avg} = 0A$$

Output Capacitor Voltage:

$$V_{C_o} = V_{out}$$

# Cuk Converter

A Cuk regulator converts a positive input voltage to a higher or lower negative output voltage level. The energy is transferred to the output when the FET is not conducting.

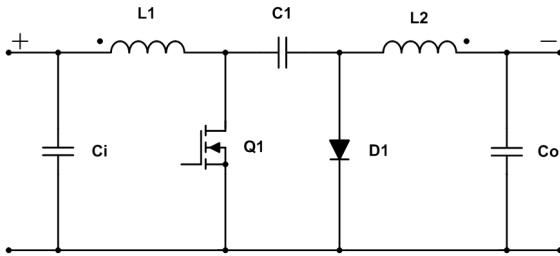


Figure 7.0.1. Schematic of a Cuk converter

## 7.1. General

$$\text{Right Half Plane Zero: } f_{rhpz} = \frac{1}{2\pi} \cdot \sqrt{\frac{1-D}{L_1 \cdot C_1}}$$

### 7.1.1. Continuous Conduction Mode.

FET on, increasing current:

$$t_1 = \frac{1}{f_{switch}} \cdot \frac{-V_{out} + V_f}{-V_{out} + V_{in} + V_f}$$

FET off, decreasing current:

$$t_2 = \frac{1}{f_{switch}} - t_1$$

Average Input Current:

$$I_{in,avg} = \frac{(V_{out} - V_f) \cdot I_{out}}{V_{in}}$$

Inductor  $L_1$  Ripple:

$$I_{L_1,ripple} = V_{in} \cdot \frac{t_1}{L_1}$$

Inductor  $L_2$  Ripple:

$$I_{L_2,ripple} = V_{in} \cdot \frac{t_1}{L_2}$$

Coupling Capacitor  $C_1$  Voltage Ripple:

$$V_{C_1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$$

### 7.1.2. Discontinuous Conduction Mode.

FET on, increasing current:

$$t_1 = \frac{V_{in} \cdot \sqrt{2 \cdot (-I_{out}) \cdot |V_{out} - V_f| \cdot (V_{in} - V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2) \cdot (V_{in} + |V_{out} - V_f|) \cdot L_1 \cdot L_2}}{(V_{in}^3 + V_{in}^2 \cdot |V_{out} - V_f|) \cdot f_{switch} \cdot (L_1 + L_2)}$$

FET off, decreasing current:

$$t_2 = \frac{L_1 \cdot L_2 \cdot \sqrt{2 \cdot (-I_{out}) \cdot |V_{out} - V_f| \cdot (V_{in} - V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2) \cdot (V_{in} + |V_{out} - V_f|) \cdot \frac{1}{L_1 \cdot L_2}}}{|V_{out} - V_f| \cdot f_{switch} \cdot (L_1 + L_2) \cdot (V_{in} + |V_{out} - V_f|)}$$

FET off, constant current:

$$t_3 = \frac{1}{f_{switch}} - t_1 - t_2$$

Average Input Current:

$$I_{in,avg} = \frac{(V_{out} - V_f) \cdot I_{out}}{V_{in}}$$

Inductor  $L_1$  Ripple:

$$I_{L_1,ripple} = V_{in} \cdot \frac{t_1}{L_1}$$

Inductor  $L_2$  Ripple:

$$I_{L_2,ripple} = V_{in} \cdot \frac{t_1}{L_2}$$

Coupling Capacitor  $C_1$  Voltage Ripple:

$$V_{C_1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$$

## 7.2. Inductor $L_1$

### 7.2.1. CCM & DCM.

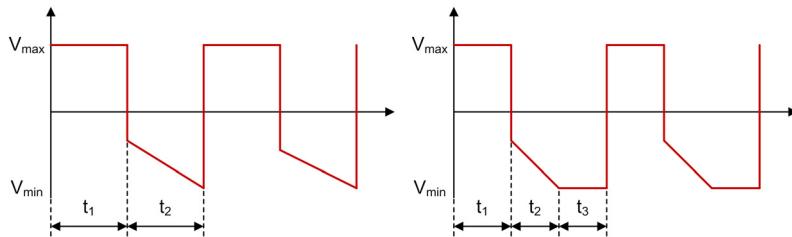


Figure 7.2.1. Cuk - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

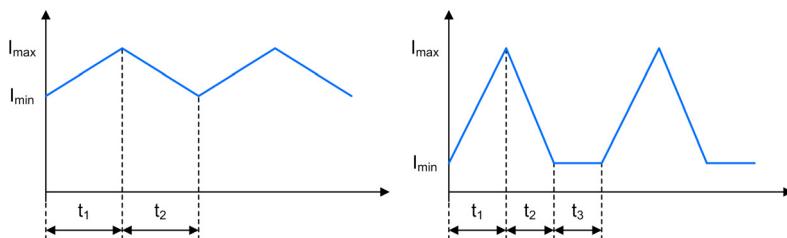


Figure 7.2.2. Cuk - Inductor  $L_1$  Current Waveforms in CCM and DCM

$$\text{Min. Inductor Current: } I_{L1,min} = I_{in,avg} - \frac{1}{2} \cdot I_{L1,ripple} \cdot (t_1 + t_2) \cdot f_{switch}$$

$$\text{Max. Inductor Current: } I_{L1,max} = I_{L1,min} + I_{L1,ripple}$$

$$\text{Average Inductor Current: } I_{L1,avg} = I_{in,avg}$$

$$\text{Inductor Voltage during } t_1: \quad V_{L1,t_1} = V_{in}$$

$$\text{Min. Inductor Voltage during } t_2: \quad V_{L1,min,t_2} = V_{out} - V_f - \frac{V_{C1,ripple}}{2}$$

$$\text{Max. Inductor Voltage during } t_2: \quad V_{L1,max,t_2} = V_{out} - V_f + \frac{V_{C1,ripple}}{2}$$

$$\text{Inductor Voltage during } t_3: \quad V_{L1,t_3} = 0V$$

The offset in DCM during  $t_3$  is dependent on the input voltage and can be positive or negative.

### 7.3. Inductor $L_2$

#### 7.3.1. CCM.

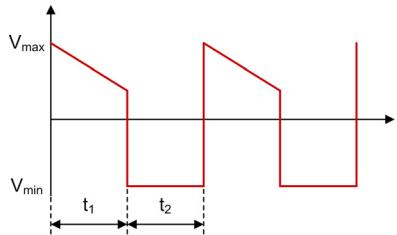


Figure 7.3.1. Cuk - Inductor  $L_2$  Voltage Waveform in CCM

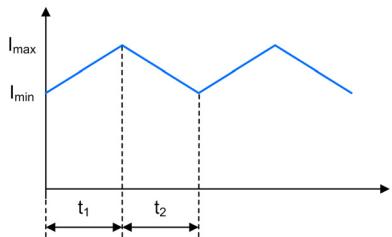


Figure 7.3.2. Cuk - Inductor  $L_2$  Current Waveform in CCM

Max. Inductor Current:  $I_{L_2,max} = I_{out} + \frac{I_{L_2,ripple}}{2}$

Min. Inductor Current:  $I_{L_2,min} = I_{L_2,max} - I_{L_2,ripple}$

Average Inductor Current:  $I_{L_2,avg} = I_{out}$

Min. Inductor Voltage during  $t_1$ :  $V_{L_2,min,t_1} = -V_{in} - \frac{V_{C_1,ripple}}{2}$

Max. Inductor Voltage during  $t_1$ :  $V_{L_2,max,t_1} = -V_{in} + \frac{V_{C_1,ripple}}{2}$

Inductor Voltage during  $t_2$ :  $V_{L_2,t_2} = V_{out} - V_f$

### 7.3.2. DCM.

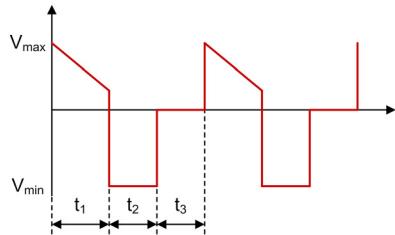


Figure 7.3.3. Cuk - Inductor  $L_2$  Voltage Waveform in DCM

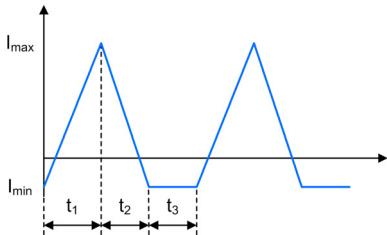


Figure 7.3.4. Cuk - Inductor  $L_2$  Current Waveform in DCM

$$\text{Min. Inductor Current: } I_{L_2,min} = -I_{L_1,min}$$

$$\text{Max. Inductor Current: } I_{L_2,max} = I_{L_2,min} + I_{L_2,ripple}$$

$$\text{Average Inductor Current: } I_{L_2,avg} = I_{out}$$

$$\text{Min. Inductor Voltage during } t_1: \quad V_{L_2,min,t_1} = -V_{in} - \frac{V_{C_1,ripple}}{2}$$

$$\text{Max. Inductor Voltage during } t_1: \quad V_{L_2,max,t_1} = -V_{in} + \frac{V_{C_1,ripple}}{2}$$

$$\text{Inductor Voltage during } t_2: \quad V_{L_2,t_2} = V_{out} - V_f$$

$$\text{Inductor Voltage during } t_3: \quad V_{L_2,t_3} = 0V$$

The offset of the current in DCM during  $t_3$  is dependent on the input voltage and can be positive or negative.

## 7.4. FET $Q_1$

### 7.4.1. CCM & DCM.

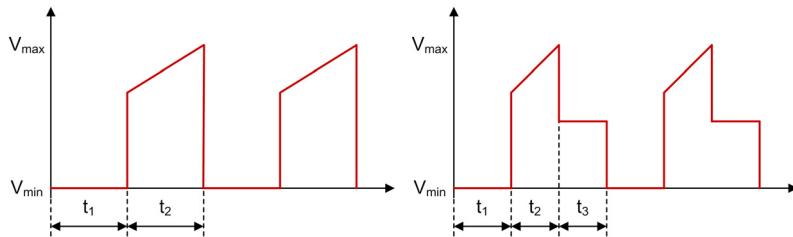


Figure 7.4.1. Cuk - FET  $Q_1$  Voltage Waveforms in CCM and DCM

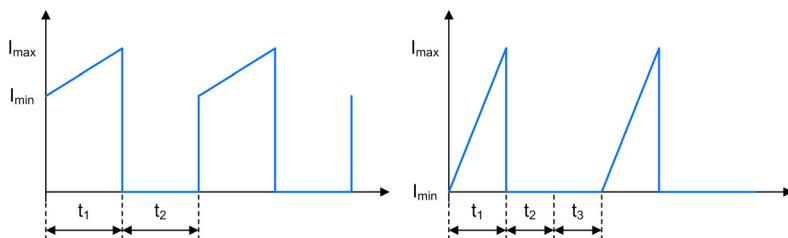


Figure 7.4.2. Cuk - FET  $Q_1$  Current Waveforms in CCM and DCM

Min. FET Current:  $I_{Q_1,min} = I_{L_1,min} - I_{L_2,max}$

Max. FET Current:  $I_{Q_1,max} = I_{L_1,max} - I_{L_2,min}$

Average FET Current:  $I_{Q_1,avg} = I_{in,avg}$

FET Voltage during  $t_1$ :  $V_{Q_1,t_1} = 0V$

Min. FET Voltage during  $t_2$ :  $V_{Q_1,min,t_2} = V_{in} - V_{out} + V_f - \frac{V_{C_1,ripple}}{2}$

Max. FET Voltage during  $t_2$ :  $V_{Q_1,max,t_2} = V_{in} - V_{out} + V_f + \frac{V_{C_1,ripple}}{2}$

FET Voltage during  $t_3$ :  $V_{Q_1,t_3} = V_{in}$

## 7.5. Diode $D_1$

### 7.5.1. CCM & DCM.

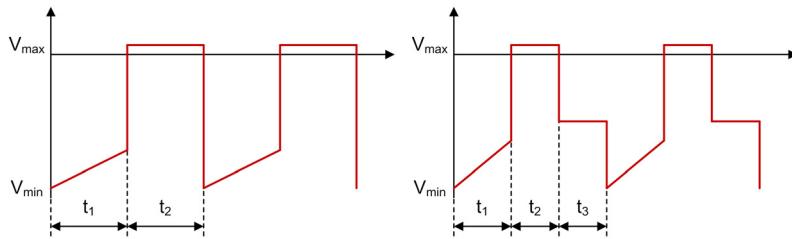


Figure 7.5.1. Cuk - Diode  $D_1$  Voltage Waveforms in CCM and DCM

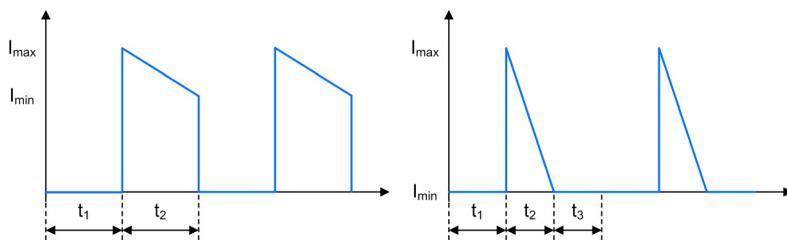


Figure 7.5.2. Cuk - Diode  $D_1$  Current Waveforms in CCM and DCM

$$\text{Min. Diode Current: } I_{D_1,min} = I_{L_1,min} - I_{L_2,max}$$

$$\text{Max. Diode Current: } I_{D_1,max} = I_{L_1,max} - I_{L_2,min}$$

$$\text{Average Diode Current: } I_{D_1,avg} = I_{out}$$

$$\text{Min. Diode Voltage during } t_1: \quad V_{D_1,min,t_1} = -V_{in} + V_{out} - \frac{V_{C_1,ripple}}{2}$$

$$\text{Max. Diode Voltage during } t_1: \quad V_{D_1,max,t_1} = -V_{in} + V_{out} + \frac{V_{C_1,ripple}}{2}$$

$$\text{Diode Voltage during } t_2: \quad V_{D_1,t_2} = V_f$$

$$\text{Diode Voltage during } t_3: \quad V_{D_1,t_3} = V_{out}$$

## 7.6. Coupling Capacitor $C_1$

### 7.6.1. CCM & DCM.

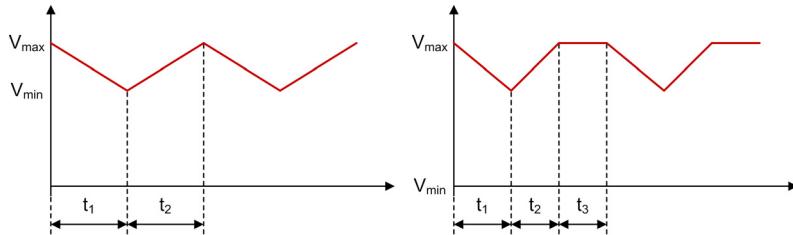


Figure 7.6.1. Cuk - Coupling Capacitor  $C_1$  Voltage Waveforms in CCM and DCM

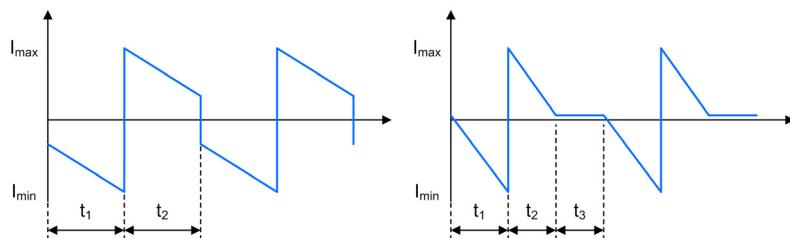


Figure 7.6.2. Cuk - Coupling Capacitor  $C_1$  Current Waveforms in CCM and DCM

Min. Coupling Capacitor Current during  $t_1$ :  $I_{C_1,min,t_1} = I_{L_1,max} - I_{fet,max}$

Max. Coupling Capacitor Current during  $t_1$ :  $I_{C_1,max,t_1} = I_{L_1,min} - I_{fet,min}$

Min. Coupling Capacitor Current during  $t_2$ :  $I_{C_1,min,t_2} = I_{L_1,min}$

Max. Coupling Capacitor Current during  $t_2$ :  $I_{C_1,max,t_2} = I_{L_1,max}$

Average Coupling Capacitor Current:  $I_{C_1,avg} = 0A$

Min. Coupling Capacitor Voltage:  $V_{C_1,min} = V_{in} - V_{out} - \frac{V_{C_1,ripple}}{2}$

Max. Coupling Capacitor Voltage:  $V_{C_1,max} = V_{in} - V_{out} + \frac{V_{C_1,ripple}}{2}$

Coupling Capacitor Voltage during  $t_3$ :  $V_{C_1,t_3} = V_{in} - V_{out} + \frac{V_{C_1,ripple}}{2}$

## 7.7. Input Capacitor $C_i$

### 7.7.1. CCM & DCM.

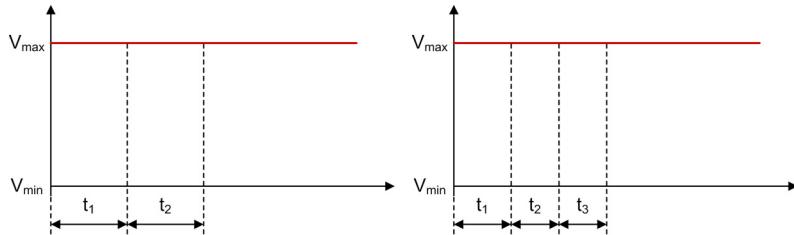


Figure 7.7.1. Cuk - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

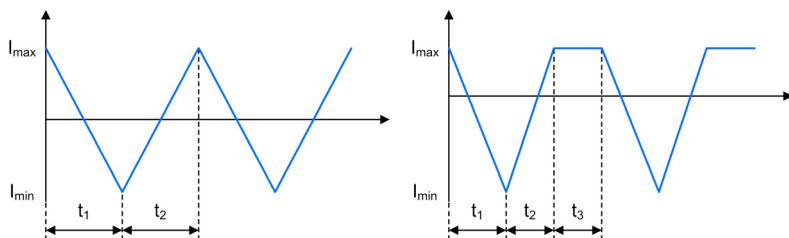


Figure 7.7.2. Cuk - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current: } I_{C_i,min} = I_{in,avg} - I_{L1,max}$$

$$\text{Max. Input Capacitor Current: } I_{C_i,max} = I_{in,avg} - I_{L1,min}$$

$$\text{Average Input Capacitor Current: } I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage: } V_{C_i} = V_{in}$$

## 7.8. Output Capacitor $C_o$

### 7.8.1. CCM & DCM.

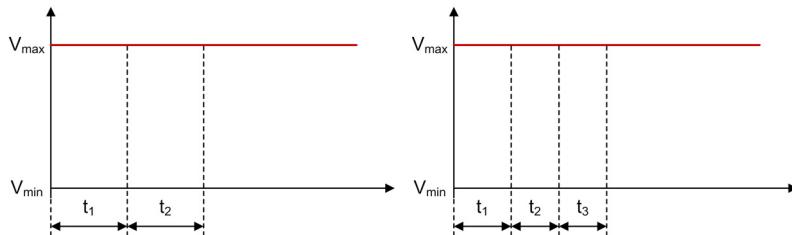


Figure 7.8.1. Cuk - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

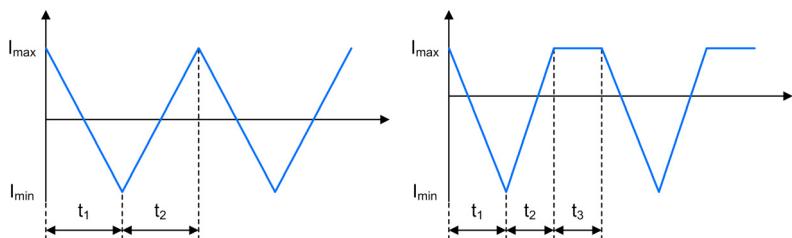


Figure 7.8.2. Cuk - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

$$\text{Min. Output Capacitor Current: } I_{C_o,\text{min}} = -I_{out} + I_{L2,\text{min}}$$

$$\text{Max. Output Capacitor Current: } I_{C_o,\text{max}} = -I_{out} + I_{L2,\text{max}}$$

$$\text{Average Output Capacitor Current: } I_{C_o,\text{avg}} = 0A$$

$$\text{Output Capacitor Voltage: } V_{C_o} = V_{out}$$

# Zeta Converter

A Zeta converter steps up/down an input voltage to a higher/lower output voltage level. The energy is transferred to the output when the switch is conducting.

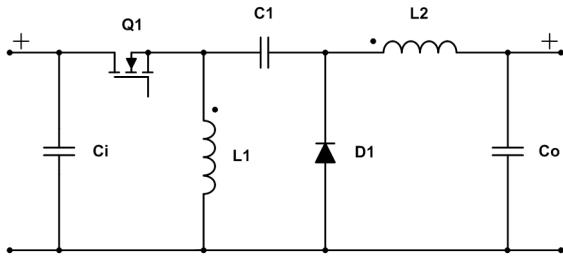


Figure 8.0.1. Schematic of a Zeta converter

## 8.1. General

### 8.1.1. Continuous Conduction Mode.

FET on, increasing current:

$$t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out} + V_f}{V_{out} + V_{in} + V_f}$$

FET off, decreasing current:

$$t_2 = \frac{1}{f_{switch}} - t_1$$

Average Input Current:

$$I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$$

Inductor  $L_1$  Ripple:

$$I_{L1,ripple} = V_{in} \cdot \frac{t_1}{L_1}$$

Inductor  $L_2$  Ripple:

$$I_{L2,ripple} = V_{in} \cdot \frac{t_1}{L_2}$$

Coupling Capacitor  $C_1$  Voltage Ripple:

$$V_{C1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$$

### 8.1.2. Discontinuous Conduction Mode.

FET on, increasing current:

$$t_1 = \frac{\sqrt{2 \cdot I_{out} \cdot L_1 \cdot L_2 \cdot (V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2)}}{V_{in} \cdot f_{switch} \cdot (L_1 + L_2)}$$

FET off, decreasing current:

$$t_2 = \frac{\sqrt{2 \cdot I_{out} \cdot L_1 \cdot L_2 \cdot (V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2)}}{(V_{out} + V_f) \cdot f_{switch} \cdot (L_1 + L_2)}$$

FET off, constant current:

$$t_3 = \frac{1}{f_{switch}} - t_1 - t_2$$

Average Input Current:

$$I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$$

Inductor  $L_1$  Ripple:

$$I_{L1,ripple} = V_{in} \cdot \frac{t_1}{L_1}$$

Inductor  $L_2$  Ripple:

$$I_{L2,ripple} = V_{in} \cdot \frac{t_1}{L_2}$$

Coupling Capacitor  $C_1$  Voltage Ripple:

$$V_{C1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$$

## 8.2. Inductor $L_1$

### 8.2.1. CCM & DCM.

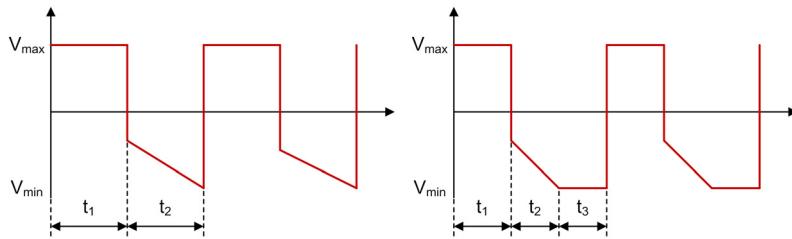


Figure 8.2.1. Zeta - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

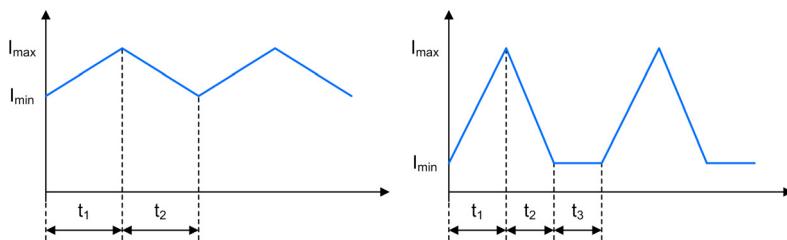


Figure 8.2.2. Zeta - Inductor  $L_1$  Current Waveforms in CCM and DCM

Min. Inductor Current:  $I_{L1,min} = I_{in,avg} - \frac{1}{2} \cdot I_{L1,ripple} \cdot (t_1 + t_2) \cdot f_{switch}$

Max. Inductor Current:  $I_{L1,max} = I_{L1,min} + I_{L1,ripple}$

Average Inductor Current:  $I_{L1,avg} = I_{in,avg}$

Inductor Voltage during  $t_1$ :  $V_{L1,on} = V_{in}$

Min. Inductor Voltage during  $t_2$ :  $V_{L1,min,t2} = -V_{out} - V_f - \frac{V_{C1,ripple}}{2}$

Max. Inductor Voltage during  $t_2$ :  $V_{L1,max,t2} = -V_{out} - V_f + \frac{V_{C1,ripple}}{2}$

Inductor Voltage during  $t_3$ :  $V_{L1,t3} = 0V$

The offset of the current in DCM during  $t_3$  is dependent on the input voltage and can be positive or negative.

### 8.3. Inductor $L_2$

#### 8.3.1. CCM.

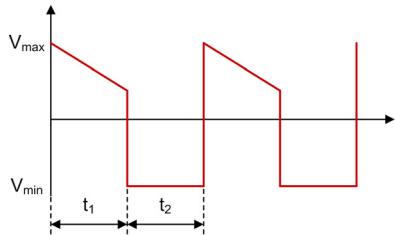


Figure 8.3.1. Zeta - Inductor  $L_2$  Voltage Waveform in CCM

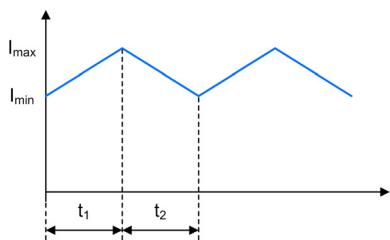


Figure 8.3.2. Zeta - Inductor  $L_2$  Current Waveform in CCM

$$\text{Min. Inductor Current: } I_{L_2,min} = I_{out} - \frac{I_{L_2,ripple}}{2}$$

$$\text{Max. Inductor Current: } I_{L_2,max} = I_{L_2,min} + I_{L_2,ripple}$$

$$\text{Average Inductor Current: } I_{L_2,avg} = I_{out}$$

$$\text{Min. Inductor Voltage during } t_1: V_{L_2,min,t_1} = V_{in} - \frac{V_{C_1,ripple}}{2}$$

$$\text{Max. Inductor Voltage during } t_1: V_{L_2,max,t_1} = V_{in} + \frac{V_{C_1,ripple}}{2}$$

$$\text{Inductor Voltage during } t_2: V_{L_2,t_2} = -V_{out} - V_f$$

### 8.3.2. DCM.

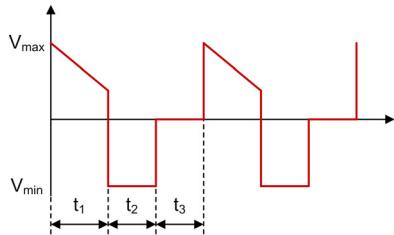


Figure 8.3.3. Zeta - Inductor  $L_2$  Voltage Waveform in DCM

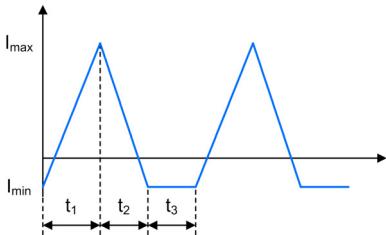


Figure 8.3.4. Zeta - Inductor  $L_2$  Current Waveform in DCM

$$\text{Min. Inductor Current: } I_{L_2,\min} = -I_{L_1,\min}$$

$$\text{Max. Inductor Current: } I_{L_2,\max} = I_{L_2,\min} + I_{L_2,\text{ripple}}$$

$$\text{Average Inductor Current: } I_{L_2,\text{avg}} = I_{\text{out}}$$

$$\text{Min. Inductor Voltage during } t_1: \quad V_{L_2,\min,t_1} = V_{\text{in}} - \frac{V_{C_1,\text{ripple}}}{2}$$

$$\text{Max. Inductor Voltage during } t_1: \quad V_{L_2,\max,t_1} = V_{\text{in}} + \frac{V_{C_1,\text{ripple}}}{2}$$

$$\text{Inductor Voltage during } t_2: \quad V_{L_2,t_2} = -V_{\text{out}} - V_f$$

$$\text{Inductor Voltage during } t_3: \quad V_{L_2,t_3} = 0V$$

The offset of the current in DCM during  $t_3$  is dependent on the input voltage and can be positive or negative.

## 8.4. FET $Q_1$

### 8.4.1. CCM & DCM.

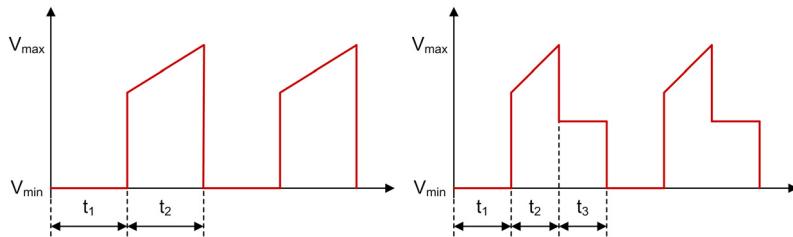


Figure 8.4.1. Zeta - FET  $Q_1$  Voltage Waveforms in CCM and DCM

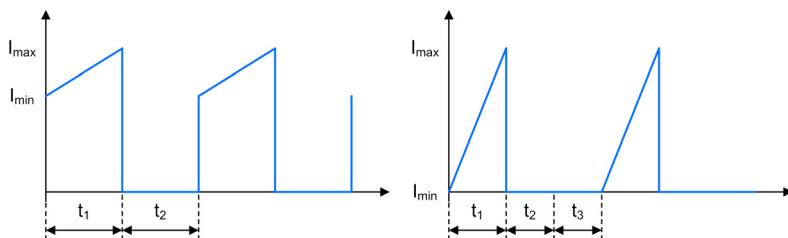


Figure 8.4.2. Zeta - FET  $Q_1$  Current Waveforms in CCM and DCM

$$\text{Min. FET Current: } I_{Q_1,min} = I_{L_1,min} + I_{L_2,min}$$

$$\text{Max. FET Current: } I_{Q_1,max} = I_{L_1,max} + I_{L_2,max}$$

$$\text{Average FET Current: } I_{Q_1,avg} = I_{in,avg}$$

$$\text{FET Voltage during } t_1: \quad V_{Q_1,t_1} = 0V$$

$$\text{Min. FET Voltage during } t_2: \quad V_{Q_1,min,t_2} = V_{in} + V_{out} + V_f - \frac{V_{C_1,ripple}}{2}$$

$$\text{Max. FET Voltage during } t_2: \quad V_{Q_1,max,t_2} = V_{in} + V_{out} + V_f + \frac{V_{C_1,ripple}}{2}$$

$$\text{FET Voltage during } t_3: \quad V_{Q_1,t_3} = V_{in}$$

## 8.5. Diode $D_1$

### 8.5.1. CCM & DCM.

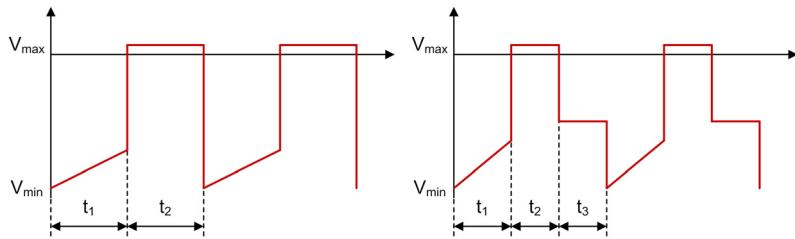


Figure 8.5.1. Zeta - Diode  $D_1$  Voltage Waveforms in CCM and DCM

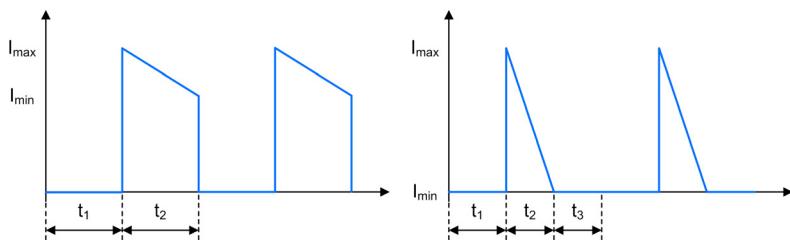


Figure 8.5.2. Zeta - Diode  $D_1$  Current Waveforms in CCM and DCM

$$\text{Min. Diode Current: } I_{D1,min} = I_{L1,min} + I_{L2,min}$$

$$\text{Max. Diode Current: } I_{D1,max} = I_{L1,max} + I_{L2,max}$$

$$\text{Average Diode Current: } I_{D1,avg} = I_{out}$$

$$\text{Min. Diode Voltage during } t_1: \quad V_{D1,min,t_1} = -V_{in} - V_{out} - \frac{V_{C1,ripple}}{2}$$

$$\text{Max. Diode Voltage during } t_1: \quad V_{D1,max,t_1} = -V_{in} - V_{out} + \frac{V_{C1,ripple}}{2}$$

$$\text{Diode Voltage during } t_2: \quad V_{D1,t_2} = V_f$$

$$\text{Diode Voltage during } t_3: \quad V_{D1,t_3} = -V_{out}$$

## 8.6. Coupling Capacitor $C_1$

### 8.6.1. CCM & DCM.

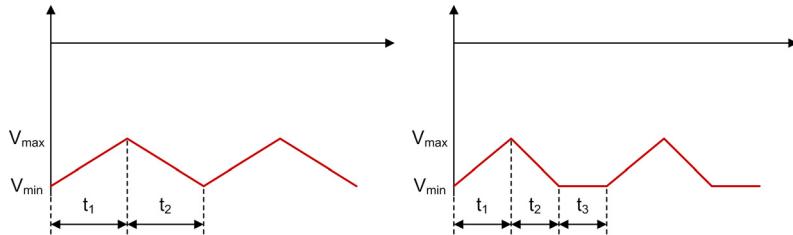


Figure 8.6.1. Zeta - Coupling Capacitor  $C_1$  Voltage Waveforms in CCM and DCM

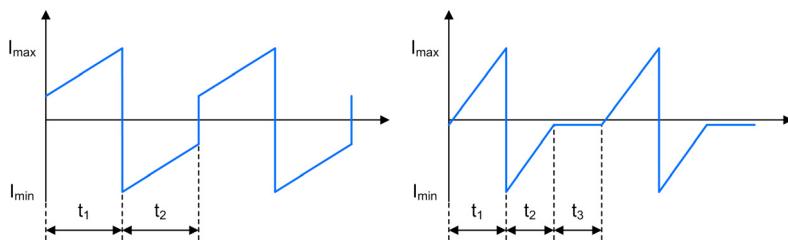


Figure 8.6.2. Zeta - Coupling Capacitor  $C_1$  Current Waveforms in CCM and DCM

Min. Coupling Capacitor Current during  $t_1$ :  $I_{C_1,min,t_1} = -I_{L_1,min} + I_{fet,min}$

Max. Coupling Capacitor Current during  $t_1$ :  $I_{C_1,max,t_1} = -I_{L_1,max} + I_{fet,max}$

Min. Coupling Capacitor Current during  $t_2$ :  $I_{C_1,min,t_2} = -I_{L_1,max}$

Max. Coupling Capacitor Current during  $t_2$ :  $I_{C_1,max,t_2} = -I_{L_1,min}$

Coupling Capacitor Current during  $t_3$ :  $I_{C_1,t_3} = -I_{L_1,min}$

Average Coupling Capacitor Current:  $I_{C_1,avg} = 0A$

Min. Coupling Capacitor Voltage:  $V_{C_1,min} = -V_{out} - \frac{V_{C_1,ripple}}{2}$

Max. Coupling Capacitor Voltage:  $V_{C_1,max} = -V_{out} + \frac{V_{C_1,ripple}}{2}$

Coupling Capacitor Voltage during  $t_3$ :  $V_{C_1,t_3} = -V_{out} - \frac{V_{C_1,ripple}}{2}$

## 8.7. Input Capacitor $C_i$

### 8.7.1. CCM & DCM.

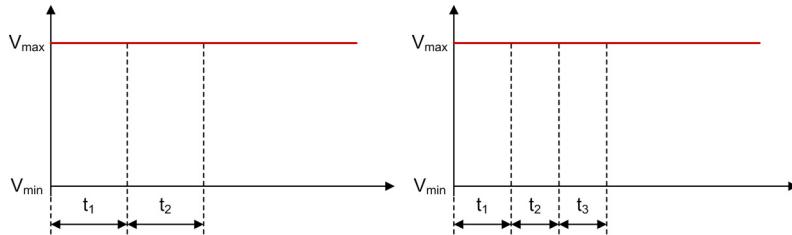


Figure 8.7.1. Zeta - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

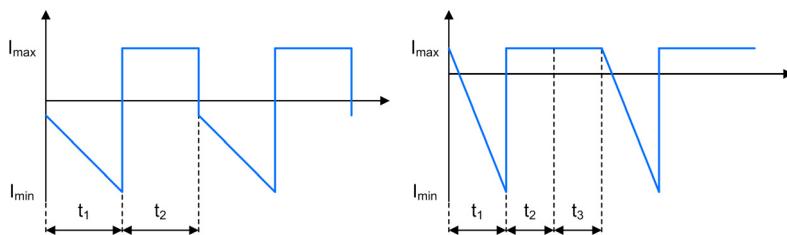


Figure 8.7.2. Zeta - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

Min. Input Capacitor Current during  $t_1$ :  $I_{C_i,min,t_1} = I_{in,avg} - I_{fet,max}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_i,max,t_1} = I_{in,avg} - I_{fet,min}$

Input Capacitor Current during  $t_2$  and  $t_3$ :  $I_{C_i,t_{2/3}} = I_{in,avg}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

## 8.8. Output Capacitor $C_o$

### 8.8.1. CCM & DCM.

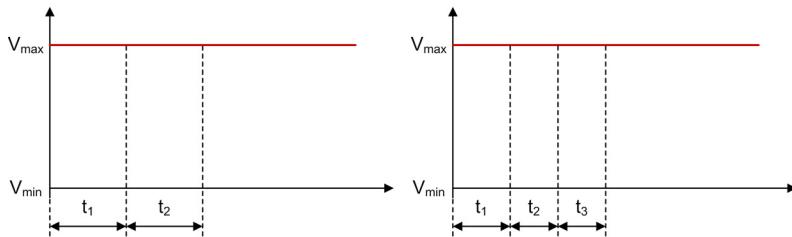


Figure 8.8.1. Zeta - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

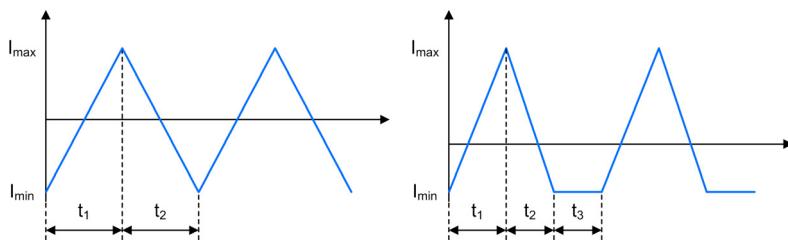


Figure 8.8.2. Zeta - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

$$\text{Min. Output Capacitor Current: } I_{C_o,min} = I_{L_2,min} - I_{out}$$

$$\text{Max. Output Capacitor Current: } I_{C_o,max} = I_{L_2,max} - I_{out}$$

$$\text{Average Output Capacitor Current: } I_{C_o,avg} = 0A$$

$$\text{Output Capacitor Voltage: } V_{C_o} = V_{out}$$

# Flyback Converter

A Flyback regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FET is not conducting.

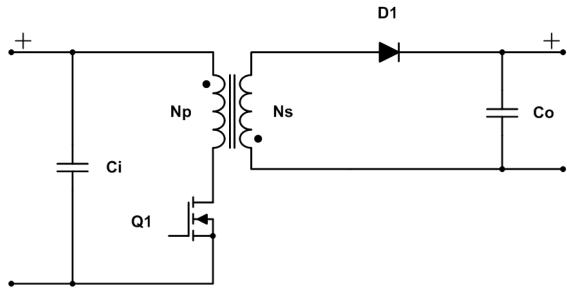


Figure 9.0.1. Schematic of a Flyback converter

### 9.1. General

$$\text{Secondary Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Primary Current Ripple: } I_{ripple} = \frac{1}{L_p} \cdot V_{in} \cdot t_1$$

$$\text{Right Half Plane Zero: } f_{rhpz} = \frac{V_{out} \cdot (1-D)^2}{2 \cdot \pi \cdot D \cdot L_s \cdot I_{out}}$$

#### 9.1.1. Continuous Conduction Mode.

$$\text{FET on, increasing current: } t_1 = \frac{1}{f_{switch}} \cdot (V_{out} + V_f) \cdot \frac{\frac{n_p}{n_s}}{V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}}$$

$$\text{FET off, decreasing current: } t_2 = \frac{1}{f_{switch}} - t_1$$

$$\text{Min. Primary Current: } I_{pri,min} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in} \cdot f_{switch} \cdot t_1} - \frac{1}{2} \cdot I_{ripple}$$

$$\text{Max. Primary Current: } I_{pri,max} = I_{pri,min} + I_{ripple}$$

$$\text{Min. Secondary Current: } I_{sec,min} = I_{pri,min} \cdot \frac{n_p}{n_s}$$

$$\text{Max. Secondary Current: } I_{sec,max} = (I_{pri,min} + I_{ripple}) \cdot \frac{n_p}{n_s}$$

$$\text{Average Input Current: } I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$$

### 9.1.2. Discontinuous Conduction Mode.

FET on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_p \cdot \frac{V_{out}+V_f}{f_{switch} \cdot V_{in}^2}}$

FET off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in}+(V_{out}+V_f) \cdot \frac{n_p}{n_s}}{(V_{out}+V_f) \cdot \frac{n_p}{n_s}} - t_1$

FET off, no current:  $t_3 = \frac{1}{f_{switch}} - t_1 - t_2$

Min. Primary Current:  $I_{pri,min} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{ripple}$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{pri,max} \cdot \frac{n_p}{n_s}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

Switching frequency:  $f_{switch,transition} = \frac{V_{in}}{2 \cdot \left( \frac{\sqrt{8} \cdot V_{in}}{\frac{n_p}{n_s} \cdot \pi \cdot V_{out}} + 1 \right)^2 \cdot I_{in} \cdot L_p}$

FET on, increasing current:  $t_1 = \frac{2 \cdot I_{in,avg} \cdot L_p}{V_{in}} \cdot \left[ \frac{\sqrt{8} \cdot V_{in}}{\frac{n_p}{n_s} \cdot \pi \cdot V_{out}} + 1 \right]$

FET off, decreasing current:  $t_2 = \frac{1}{f_{switch,transition}} - t_1$

Min. Primary Current:  $I_{pri,min} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{ripple}$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{pri,max} \cdot \frac{n_p}{n_s}$

## 9.2. Primary Side Inductor $N_p$

### 9.2.1. CCM, DCM and Transition Mode.

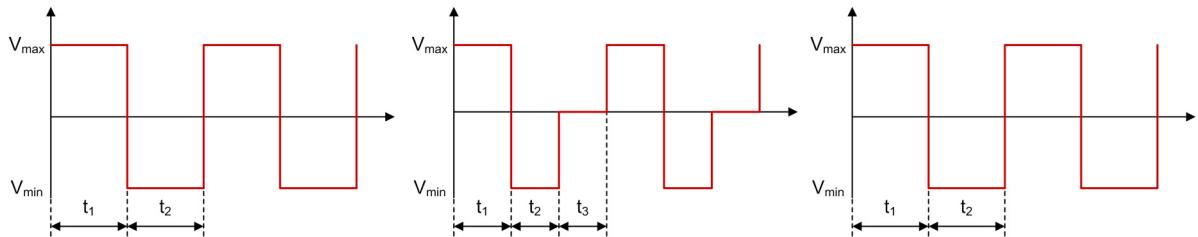


Figure 9.2.1. Flyback - Primary Side Inductor  $N_p$  Voltage Waveforms in CCM, DCM and Transition Mode

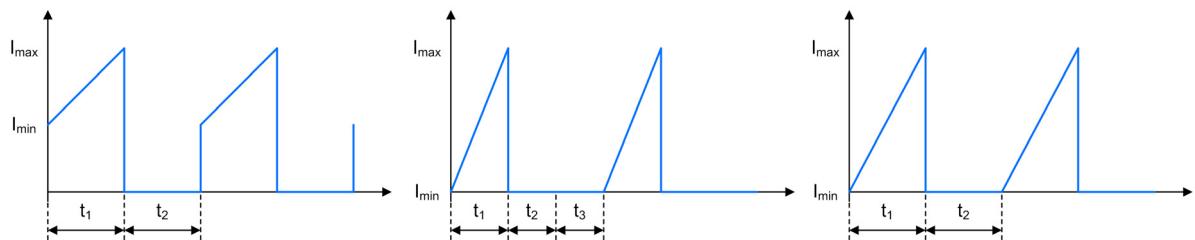


Figure 9.2.2. Flyback - Primary Side Inductor  $N_p$  Current Waveforms in CCM, DCM and Transition Mode

$$\text{Average Primary Inductor Current: } I_{N_p,\text{avg}} = \frac{I_{\text{pri},\text{min}} + I_{\text{pri},\text{max}}}{2} \cdot t_1 \cdot f_{\text{switch}}$$

$$\text{Min. Primary Inductor Current: } I_{N_p,\text{min}} = I_{\text{pri},\text{min}}$$

$$\text{Max. Primary Inductor Current: } I_{N_p,\text{max}} = I_{\text{pri},\text{max}}$$

$$\text{Min. Primary Inductor Voltage: } V_{N_p,\text{min}} = -(V_{\text{out}} + V_f) \cdot \frac{n_p}{n_s}$$

$$\text{Max. Primary Inductor Voltage: } V_{N_p,\text{max}} = V_{\text{in}}$$

$$\text{Primary Inductor Voltage during } t_3: \quad V_{N_p,t_3} = 0V$$

### 9.3. Secondary Side Inductor $N_s$

#### 9.3.1. CCM.

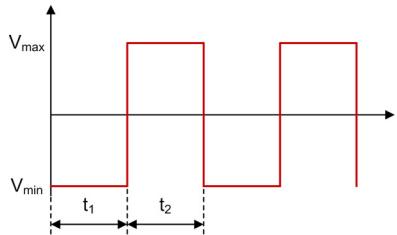


Figure 9.3.1. Flyback - Secondary Side Inductor  $N_s$  Voltage Waveform in CCM

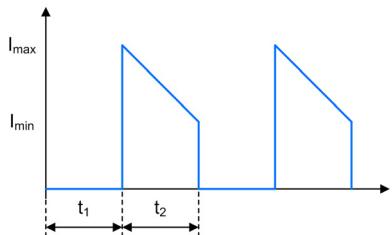


Figure 9.3.2. Flyback - Secondary Side Inductor  $N_s$  Current Waveform in CCM

Average Secondary Inductor Current:  $I_{N_s,avg} = \frac{1}{2} \cdot (I_{sec,max} + I_{sec,min}) \cdot t_2 \cdot f_{switch}$

Min. Secondary Inductor Current:  $I_{N_s,min} = I_{sec,min}$

Max. Secondary Inductor Current:  $I_{N_s,max} = I_{sec,max}$

Min. Secondary Inductor Voltage:  $V_{N_s,min} = -V_{in} \cdot \frac{n_s}{n_p}$

Max. Secondary Inductor Voltage:  $V_{N_s,max} = V_{out} + V_f$

### 9.3.2. DCM.

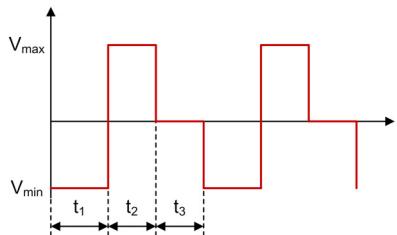


Figure 9.3.3. Flyback - Secondary Side Inductor  $N_s$  Voltage Waveform in DCM

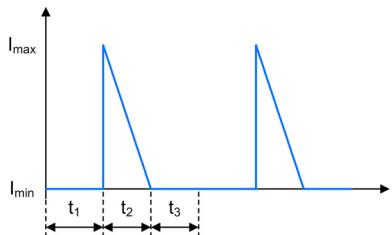


Figure 9.3.4. Flyback - Secondary Side Inductor  $N_s$  Current Waveform in DCM

Average Secondary Inductor Current:  $I_{N_s,avg} = \frac{1}{2} \cdot I_{sec,max} \cdot t_2 \cdot f_{switch}$

Min. Secondary Inductor Current:  $I_{N_s,min} = I_{sec,min}$

Max. Secondary Inductor Current:  $I_{N_s,max} = I_{sec,max}$

Min. Secondary Inductor Voltage:  $V_{N_s,min} = -V_{in} \cdot \frac{n_s}{n_p}$

Max. Secondary Inductor Voltage:  $V_{N_s,max} = V_{out} + V_f$

Secondary Inductor Voltage during  $t_3$ :  $V_{N_s,t_3} = 0V$

### 9.3.3. Transition Mode.

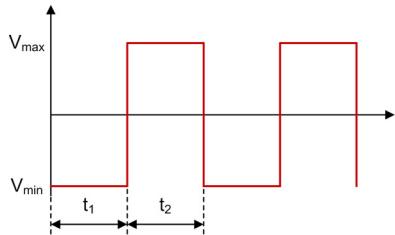


Figure 9.3.5. Flyback - Secondary Side Inductor  $N_s$  Voltage Waveform in Transition Mode

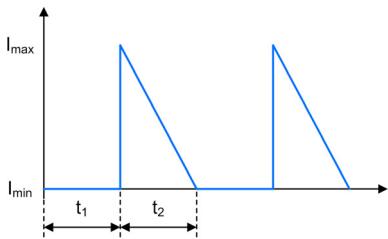


Figure 9.3.6. Flyback - Secondary Side Inductor  $N_s$  Current Waveform in Transition Mode

Average Secondary Inductor Current:  $I_{N_s,avg} = \frac{1}{2} \cdot I_{sec,max} \cdot t_2 \cdot f_{switch,transiti}$

Min. Secondary Inductor Current:  $I_{N_s,min} = I_{sec,min}$

Max. Secondary Inductor Current:  $I_{N_s,max} = I_{sec,max}$

Min. Secondary Inductor Voltage:  $V_{N_s,min} = -V_{in} \cdot \frac{n_s}{n_p}$

Max. Secondary Inductor Voltage:  $V_{N_s,max} = V_{out} + V_f$

## 9.4. FET $Q_1$

### 9.4.1. CCM, DCM and Transition Mode.

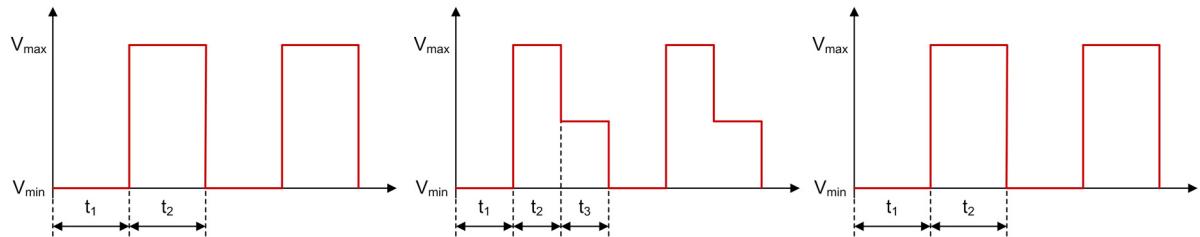


Figure 9.4.1. Flyback - FET  $Q_1$  Voltage Waveforms in CCM, DCM and Transition Mode

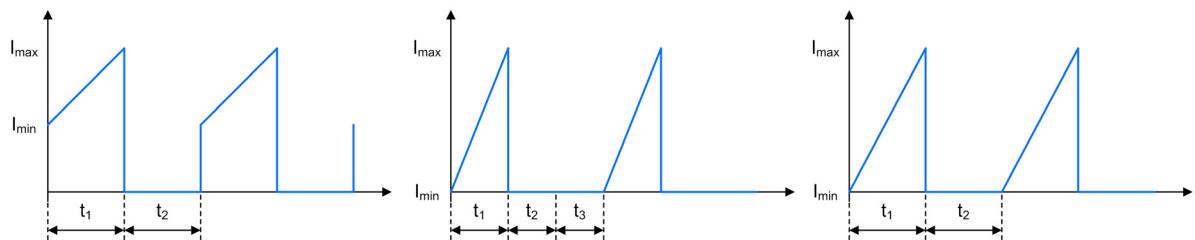


Figure 9.4.2. Flyback - FET  $Q_1$  Current Waveforms in CCM, DCM and Transition Mode

Average FET Current:  $I_{Q_1,avg} = I_{N_p,avg}$

Min. FET Current:  $I_{Q_1,min} = I_{pri,min}$

Max. FET Current:  $I_{Q_1,max} = I_{pri,max}$

Min .FET Voltage:  $V_{Q_1,min} = 0V$

Max. FET Voltage:  $V_{Q_1,max} = V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

FET Voltage during  $t_3$ :  $V_{Q_1,t_3} = V_{in}$

## 9.5. Diode $D_1$

### 9.5.1. CCM, DCM and Transition Mode.

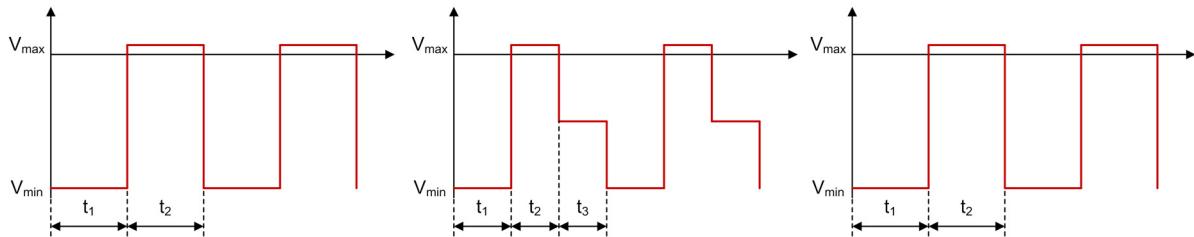


Figure 9.5.1. Flyback - Diode  $D_1$  Voltage Waveforms in CCM, DCM and Transition Mode

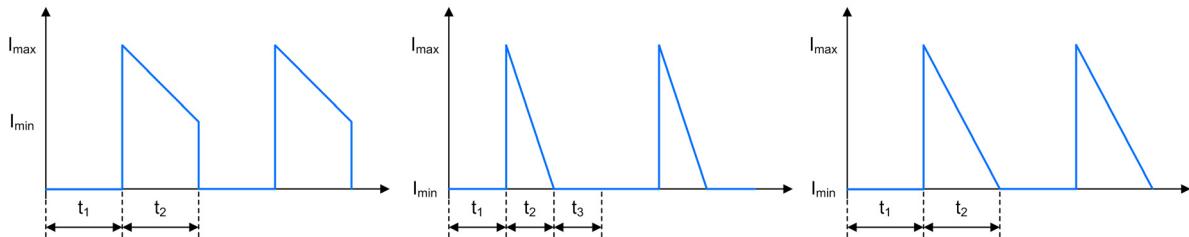


Figure 9.5.2. Flyback - Diode  $D_1$  Current Waveforms in CCM, DCM and Transition Mode

$$\text{Average Diode Current: } I_{D_1,\text{avg}} = I_{N_s,\text{avg}}$$

$$\text{Min. Diode Current: } I_{D_1,\text{min}} = I_{\text{sec},\text{min}}$$

$$\text{Max. Diode Current: } I_{D_1,\text{max}} = I_{\text{sec},\text{max}}$$

$$\text{Min. Diode Voltage: } V_{D_1,\text{min}} = -V_{\text{out}} - V_{\text{in}} \cdot \frac{n_s}{n_p}$$

$$\text{Max. Diode Voltage: } V_{D_1,\text{max}} = V_f$$

$$\text{Diode Voltage during } t_3: \quad V_{D_1,t_3} = -V_{\text{out}}$$

## 9.6. Input Capacitor $C_i$

### 9.6.1. CCM.

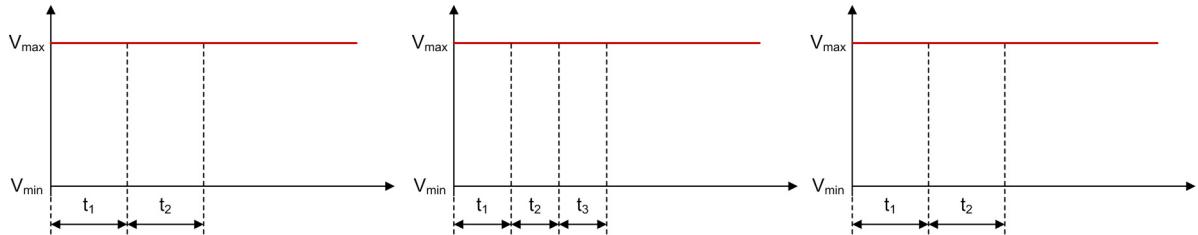


Figure 9.6.1. Flyback - Input Capacitor  $C_i$  Voltage Waveforms in CCM, DCM and Transition Mode

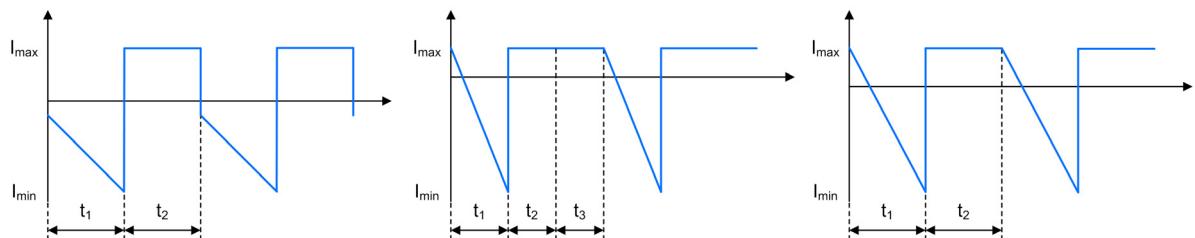


Figure 9.6.2. Flyback - Input Capacitor  $C_i$  Current Waveforms in CCM, DCM and Transition Mode

Min. Input Capacitor Current during  $t_1$ :  $I_{C_i,min,t_1} = -I_{pri,max} + I_{in,avg}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_i,max,t_1} = -I_{pri,min} + I_{in,avg}$

Input Capacitor Current during  $t_2$  and  $t_3$ :  $I_{C_i,t_{2/3}} = I_{in,avg}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

## 9.7. Output Capacitor $C_o$

### 9.7.1. CCM, DCM & Transition Mode.

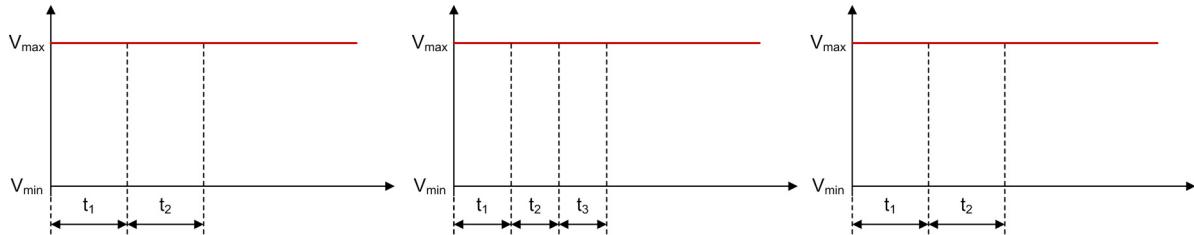


Figure 9.7.1. Flyback - Output Capacitor  $C_o$  Voltage Waveforms in CCM, DCM and Transition Mode

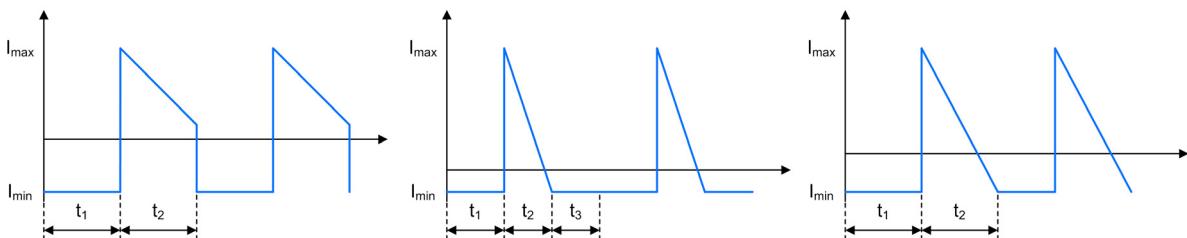


Figure 9.7.2. Flyback - Output Capacitor  $C_o$  Current Waveforms in CCM, DCM and Transition Mode

Output Capacitor Current during  $t_1$ :

$$I_{C_o,t_1} = -I_{out}$$

Min. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,min,t_{2/3}} = I_{sec,min} - I_{out}$$

Max. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,max,t_{2/3}} = I_{sec,max} - I_{out}$$

Average Output Capacitor Current:

$$I_{C_o,avg} = 0A$$

Output Capacitor Voltage:

$$V_{C_o} = V_{out}$$



# Two Switch Flyback Converter

A Two Switch Flyback regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FETs are not conducting.

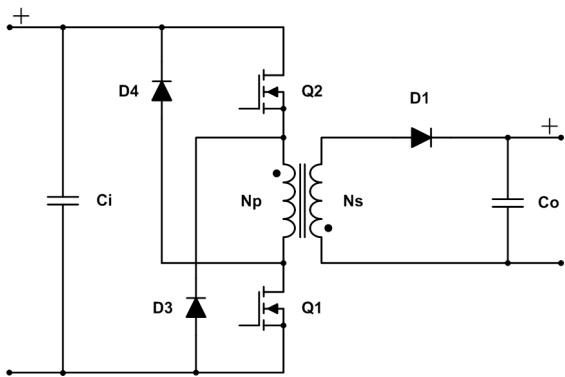


Figure 10.0.1. Schematic of a Two Switch Flyback converter

### 10.1. General

$$\text{Secondary Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Primary Current Ripple: } I_{ripple} = \frac{1}{L_p} \cdot V_{in} \cdot t_1$$

$$\text{Right Half Plane Zero: } f_{rhpz} = \frac{V_{out} \cdot (1-D)^2}{2 \cdot \pi \cdot D \cdot L_s \cdot I_{out}}$$

**10.1.1. Continuous Conduction Mode.**

FETs on, increasing current:  $t_1 = \frac{1}{f_{switch}} \cdot (V_{out} + V_f) \cdot \frac{\frac{n_p}{n_s}}{V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}}$

FETs off, decreasing current:  $t_2 = \frac{1}{f_{switch}} - t_1$

Min. Primary Current:  $I_{pri,min} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in} \cdot f_{switch} \cdot t_1} - \frac{1}{2} \cdot I_{ripple}$

Max. Primary Current:  $I_{pri,max} = I_{pri,min} + I_{ripple}$

Min. Secondary Current:  $I_{sec,min} = I_{pri,min} \cdot \frac{n_p}{n_s}$

Max. Secondary Current:  $I_{sec,max} = (I_{pri,min} + I_{ripple}) \cdot \frac{n_p}{n_s}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

**10.1.2. Discontinuous Conduction Mode.**

FETs on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_p \cdot \frac{V_{out} + V_f}{f_{switch} \cdot V_{in}^2}}$

FETs off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}}{(V_{out} + V_f) \cdot \frac{n_p}{n_s}} - t_1$

FETs off, no current:  $t_3 = \frac{1}{f_{switch}} - t_1 - t_2$

Min. Primary Current:  $I_{pri,min} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{ripple}$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{pri,max} \cdot \frac{n_p}{n_s}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

## 10.2. Primary Side Inductor $N_p$

### 10.2.1. CCM & DCM.

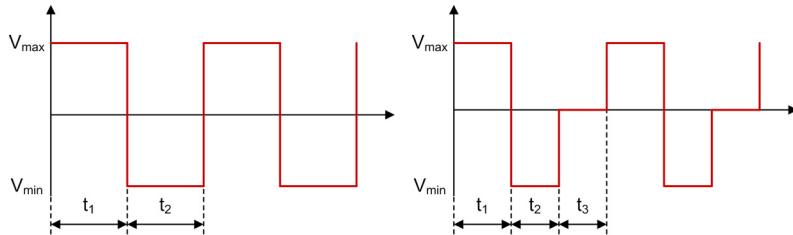


Figure 10.2.1. Two Switch Flyback - Primary Side Inductor  $N_p$  Voltage Waveforms in CCM and DCM

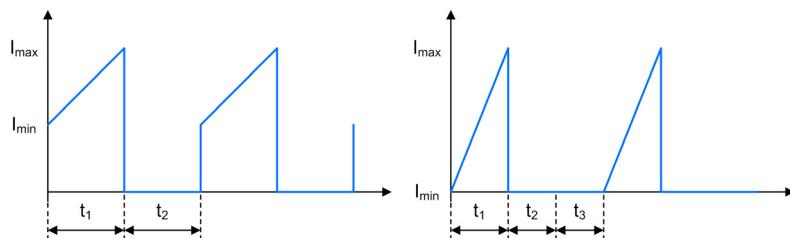


Figure 10.2.2. Two Switch Flyback - Primary Side Inductor  $N_p$  Current Waveforms in CCM and DCM

$$\text{Average Primary Inductor Current: } I_{N_p,\text{avg}} = \frac{I_{\text{pri,min}} + I_{\text{pri,max}}}{2} \cdot t_1 \cdot f_{\text{switch}}$$

$$\text{Min. Primary Inductor Current: } I_{N_p,\text{min}} = I_{\text{pri,min}}$$

$$\text{Max. Primary Inductor Current: } I_{N_p,\text{max}} = I_{\text{pri,max}}$$

$$\text{Min. Primary Inductor Voltage: } V_{N_p,\text{min}} = -(V_{\text{out}} + V_f) \cdot \frac{n_p}{n_s}$$

$$\text{Max. Primary Inductor Voltage: } V_{N_p,\text{max}} = V_{\text{in}}$$

$$\text{Primary Inductor Voltage during } t_3: \quad V_{N_p,t_3} = 0V$$

### 10.3. Secondary Side Inductor $N_s$

#### 10.3.1. CCM & DCM.

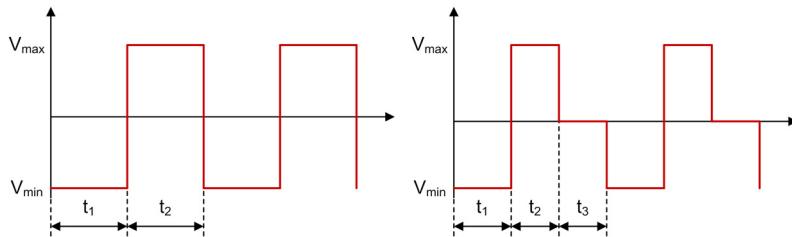


Figure 10.3.1. Two Switch Flyback - Secondary Side Inductor  $N_s$  Voltage Waveforms in CCM and DCM

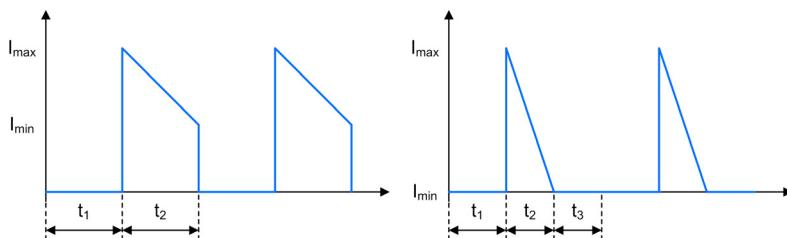


Figure 10.3.2. Two Switch Flyback - Secondary Side Inductor  $N_s$  Current Waveforms in CCM and DCM

$$\text{Average Secondary Inductor Current: } I_{N_s,avg} = \frac{I_{sec,max} + I_{sec,min}}{2} \cdot t_2 \cdot f_{switch}$$

$$\text{Min. Secondary Inductor Current: } I_{N_s,min} = I_{sec,min}$$

$$\text{Max. Secondary Inductor Current: } I_{N_s,max} = I_{sec,max}$$

$$\text{Min. Secondary Inductor Voltage: } V_{N_s,min} = -V_{in} \cdot \frac{n_s}{n_p}$$

$$\text{Max. Secondary Inductor Voltage: } V_{N_s,max} = V_{out} + V_f$$

$$\text{Secondary Inductor Voltage during } t_3: \quad V_{N_s,t_3} = 0V$$

## 10.4. FET $Q_1 / Q_2$

### 10.4.1. CCM & DCM.

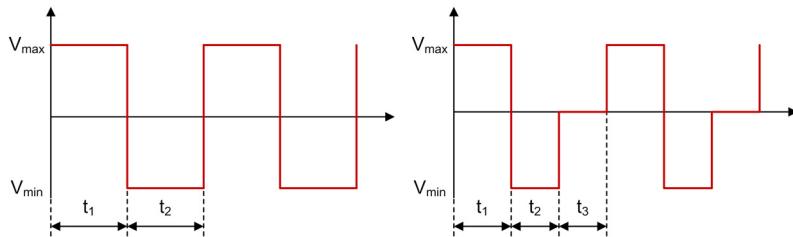


Figure 10.4.1. Two Switch Flyback - FET  $Q_1 / Q_2$  Voltage Waveforms in CCM and DCM

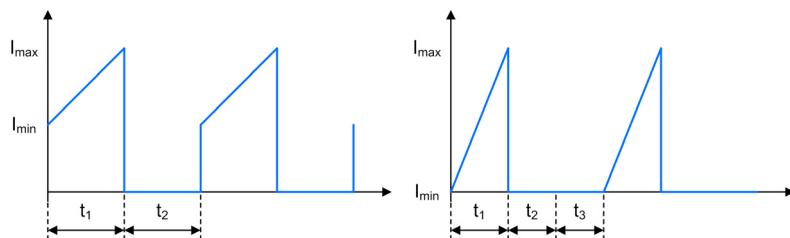


Figure 10.4.2. Two Switch Flyback - FET  $Q_1 / Q_2$  Current Waveforms in CCM and DCM

Average FET Current:  $I_{Q_{1/2},avg} = I_{in,avg}$

Min. FET Current:  $I_{Q_{1/2},min} = I_{pri,min}$

Max. FET Current:  $I_{Q_{1/2},max} = I_{pri,max}$

Min. FET Voltage:  $V_{Q_{1/2},min} = 0V$

Max. FET Voltage:  $V_{Q_{1/2},max} = \frac{V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}}{2}$

FET Voltage during  $t_3$ :  $V_{Q_{1/2},t_3} = V_{in}$

## 10.5. Diode $D_1$

### 10.5.1. CCM & DCM.

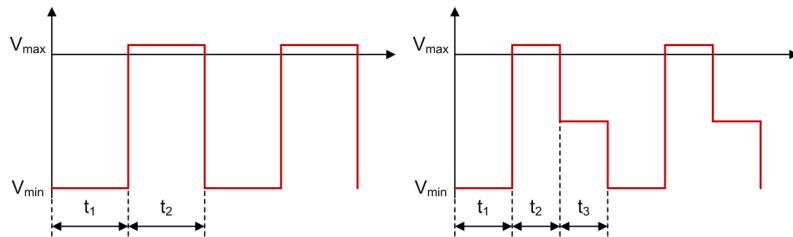


Figure 10.5.1. Two Switch Flyback - Diode  $D_1$  Voltage Waveforms in CCM and DCM

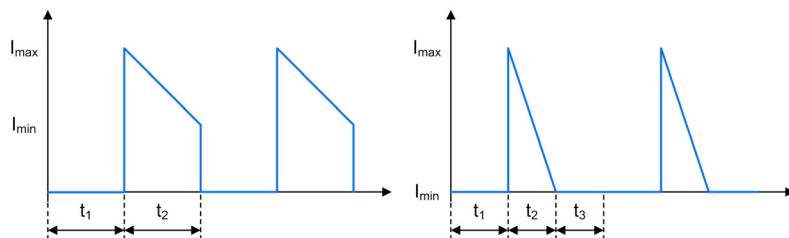


Figure 10.5.2. Two Switch Flyback - Diode  $D_1$  Current Waveforms in CCM and DCM

Average Diode Current:  $I_{D_1,avg} = I_{ind,sec,avg}$

Min. Diode Current:  $I_{D_1,min} = I_{sec,min}$

Max. Diode Current:  $I_{D_1,max} = I_{sec,max}$

Diode Voltage during  $t_1$ :  $V_{D_1,t_1} = -V_{out} - V_{in} \cdot \frac{n_s}{n_p}$

Diode Voltage during  $t_2$ :  $V_{D_1,t_2} = V_f$

Diode Voltage during  $t_3$ :  $V_{D_1,t_3} = -V_{out}$

## 10.6. Input Capacitor $C_i$

### 10.6.1. CCM & DCM.

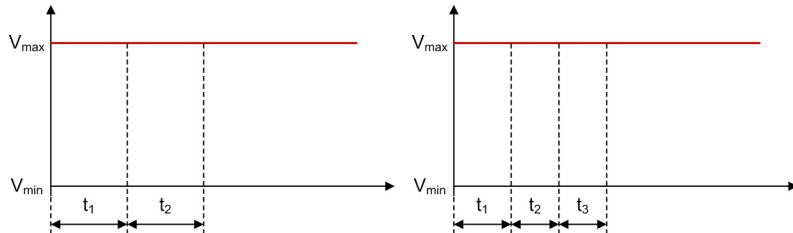


Figure 10.6.1. Two Switch Flyback - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

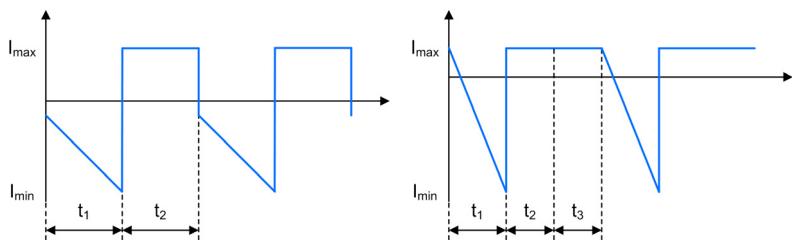


Figure 10.6.2. Two Switch Flyback - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current during } t_1: \quad I_{C_i,min,t_1} = -I_{pri,max} + I_{in,avg}$$

$$\text{Max. Input Capacitor Current during } t_1: \quad I_{C_i,max,t_1} = -I_{pri,min} + I_{in,avg}$$

$$\text{Input Capacitor Current during } t_2 \text{ and } t_3: \quad I_{C_i,t_2/3} = I_{in,avg}$$

$$\text{Average Input Capacitor Current:} \quad I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage:} \quad V_{C_i} = V_{in}$$

## 10.7. Output Capacitor $C_o$

### 10.7.1. CCM & DCM.

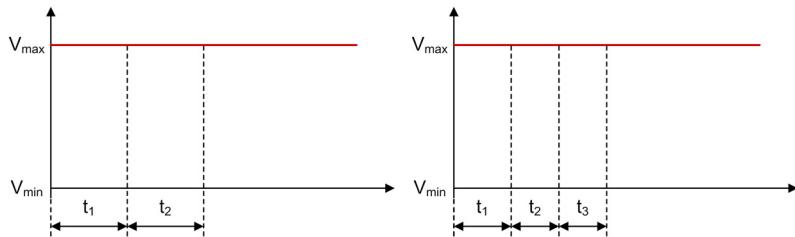


Figure 10.7.1. Two Switch Flyback - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

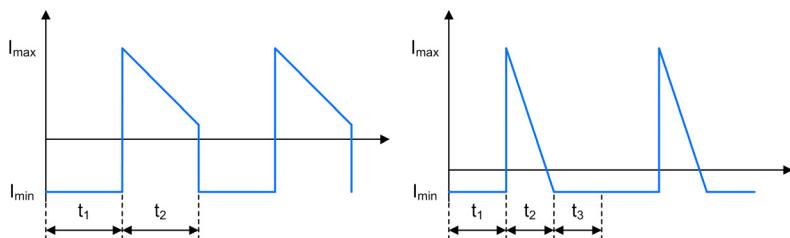


Figure 10.7.2. Two Switch Flyback - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Output Capacitor Current during  $t_1$ :

$$I_{C_o,t_1} = -I_{out}$$

Min. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,min,t_{2/3}} = I_{sec,min} - I_{out}$$

Max. Output Capacitor Current during  $t_2$  and  $t_3$ :

$$I_{C_o,max,t_{2/3}} = I_{sec,max} - I_{out}$$

Average Output Capacitor Current:

$$I_{C_o,avg} = 0A$$

Output Capacitor Voltage:

$$V_{C_o} = V_{out}$$



# Active Clamp Forward Converter

An Active Clamp Forward regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FET is conducting.

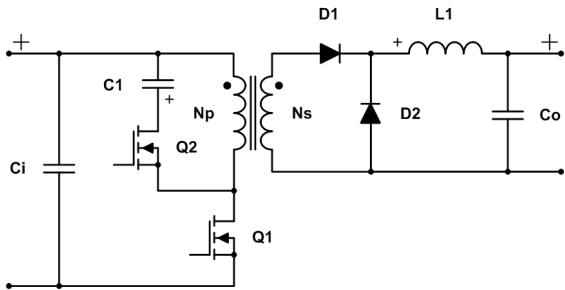


Figure 11.0.1. Schematic of an Active Clamp Forward converter

## 11.1. General

$$\text{Secondary Side Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot \left( V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out} \right) \cdot t_1$$

### 11.1.1. Continuous Conduction Mode.

FET on, increasing current:  $t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out}+V_f}{V_{in} \cdot \frac{n_s}{n_p}}$

FET off, decreasing current:  $t_2 = \frac{1}{f_{switch}} - t_1$

Magnetization Current:  $I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,min} = I_{sec,min} \cdot \frac{n_s}{n_p} - \frac{1}{2} \cdot I_{mag}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

Clamping Voltage:  $V_{clamp} = \frac{t_1 \cdot f_{switch}}{1-t_1 \cdot f_{switch}} \cdot V_{in}$

### 11.1.2. Discontinuous Conduction Mode.

FET on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot (V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

FET off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in} \cdot \frac{n_s}{n_p}}{(V_{out}+V_f)} - t_1$

FET off, no current:  $t_3 = \frac{1}{f_{switch}} - t_1 - t_2$

Magnetization Current:  $I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{ripple}$

Min. Primary Current:  $I_{pri,min} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

Clamping Voltage:  $V_{clamp} = \frac{t_1 \cdot f_{switch}}{1-t_1 \cdot f_{switch}} \cdot V_{in}$

## 11.2. Primary Side Transformer Winding $N_p$

### 11.2.1. CCM & DCM.

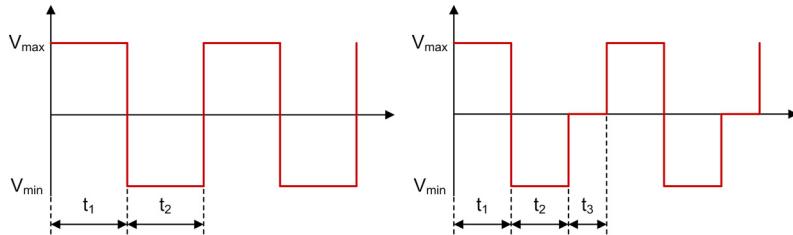


Figure 11.2.1. Active Clamp Forward - Primary Side Transformer Winding  $N_p$  Waveforms in CCM and DCM

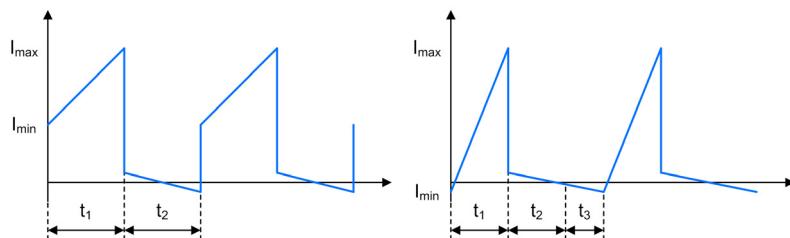


Figure 11.2.2. Active Clamp Forward - Primary Side Transformer Winding  $N_p$  Current Waveforms in CCM and DCM

Average Primary Side Transformer Current:

$$I_{N_p,avg} = \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$$

Min. Primary Side Transformer Current during  $t_1$ :

$$I_{N_p,min,t_1} = I_{pri,min}$$

Max. Primary Side Transformer Current during  $t_1$ :

$$I_{N_p,max,t_1} = I_{pri,max}$$

Min. Primary Side Transformer Current during  $t_2$  and  $t_3$ :

$$I_{N_p,min,t_{2/3}} = -\frac{1}{2} \cdot I_{mag}$$

Max. Primary Side Transformer Current during  $t_2$  and  $t_3$ :

$$I_{N_p,max,t_{2/3}} = \frac{1}{2} \cdot I_{mag}$$

Min. Primary Side Transformer Voltage:

$$V_{N_p,min} = -V_{clamp}$$

Max. Primary Side Transformer Voltage:

$$V_{N_p,max} = V_{in}$$

Primary Side Transformer Voltage during  $t_3$ :

$$V_{N_p,t_3} = 0V$$

### 11.3. Secondary Side Transformer Winding $N_s$

#### 11.3.1. CCM & DCM.

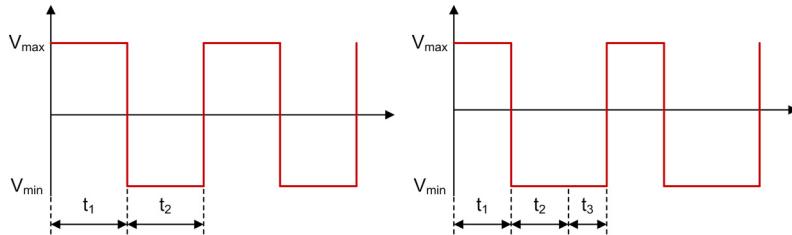


Figure 11.3.1. Active Clamp Forward - Secondary Side Transformer Winding  $N_s$  Voltage Waveforms in CCM and DCM

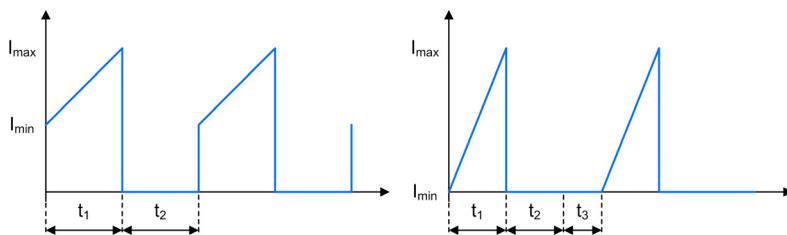


Figure 11.3.2. Active Clamp Forward - Secondary Side Transformer Winding  $N_s$  Current Waveforms in CCM and DCM

Average Secondary Side Transformer Current:  $I_{N_s,avg} = \frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 \cdot f_{switch}$

Min. Secondary Side Transformer Current:  $I_{N_s,min} = I_{sec,min}$

Max. Secondary Side Transformer Current:  $I_{N_s,max} = I_{sec,max}$

Secondary Side Transformer Voltage during  $t_1$ :  $V_{N_s,t_1} = -V_{clamp} \cdot \frac{n_s}{n_p}$

Secondary Side Transformer Voltage during  $t_{2/3}$ :  $V_{N_s,t_{2/3}} = V_{in} \cdot \frac{n_s}{n_p}$

## 11.4. Inductor $L_1$

### 11.4.1. CCM & DCM.

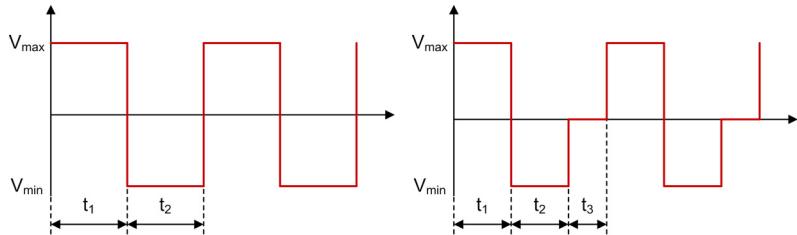


Figure 11.4.1. Active Clamp Forward - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

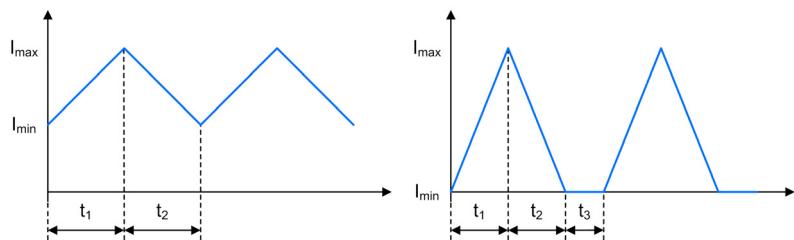


Figure 11.4.2. Active Clamp Forward - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:  $I_{L_1,avg} = \frac{I_{sec,max} + I_{sec,min}}{2} \cdot (t_1 + t_2) \cdot f_{switch}$

Min. Inductor Current:  $I_{L_1,min} = I_{trans,sec,min}$

Max. Inductor Current:  $I_{L_1,max} = I_{trans,sec,max}$

Min. Inductor Voltage:  $V_{L_1,min} = -V_{out} - V_f$

Max. Inductor Voltage:  $V_{L_1,max} = V_{in} \cdot \frac{n_s}{n_p} - V_{out} - V_f$

Inductor Voltage during  $t_3$ :  $V_{L_1,t_3} = 0V$

## 11.5. FET $Q_1$

### 11.5.1. CCM & DCM.

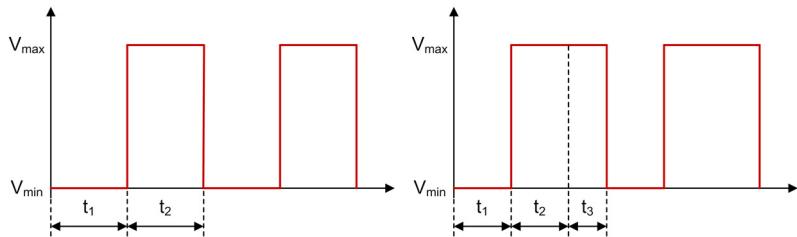


Figure 11.5.1. Active Clamp Forward - FET  $Q_1$  Voltage Waveforms in CCM and DCM

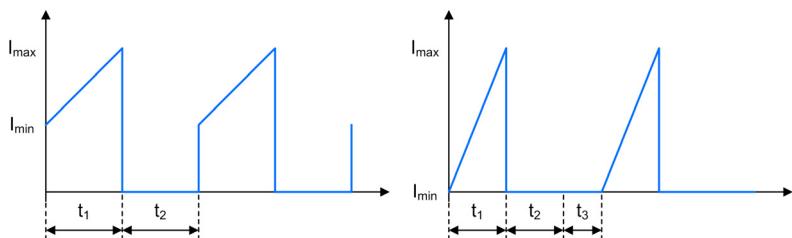


Figure 11.5.2. Active Clamp Forward - FET  $Q_1$  Current Waveforms in CCM and DCM

Average FET Current:  $I_{Q_1,avg} = I_{N_p,avg}$

Min. FET Current:  $I_{Q_1,min} = I_{pri,min}$

Max. FET Current:  $I_{Q_1,max} = I_{pri,max}$

Min. FET Voltage:  $V_{Q_1,min} = 0V$

Max. FET Voltage:  $V_{Q_1,max} = \frac{V_{in}}{1-D}$

FET Voltage during  $t_3$ :  $V_{Q_1,t_3} = 0V$

## 11.6. Clamping FET $Q_2$

### 11.6.1. CCM & DCM.

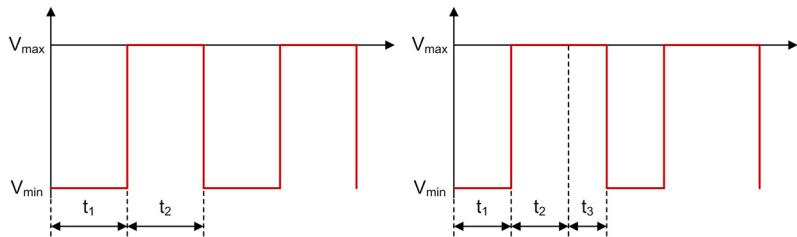


Figure 11.6.1. Active Clamp Forward - Clamping FET  $Q_2$  Voltage Waveforms in CCM and DCM

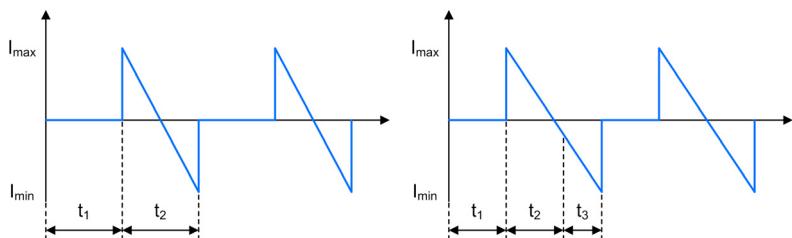


Figure 11.6.2. Active Clamp Forward - Clamping FET  $Q_2$  Current Waveforms in CCM and DCM

Average Clamping FET Current:  $I_{Q_2,avg} = 0A$

Clamping FET Current during  $t_1$ :  $I_{Q_2,t_1} = 0A$

Min. Clamping FET Current during  $t_{2/3}$ :  $I_{Q_2,min} = -\frac{1}{2} \cdot I_{mag}$

Max. Clamping FET Current during  $t_{2/3}$ :  $I_{Q_2,max} = \frac{1}{2} \cdot I_{mag}$

Min. Clamping FET Voltage:  $V_{Q_2,min} = -V_{in} - V_{clamp}$

Max. Clamping FET Voltage:  $V_{Q_2,max} = 0V$

Clamping FET Voltage during  $t_3$ :  $V_{Q_2,t_3} = 0V$

## 11.7. Clamping Capacitor $C_1$

### 11.7.1. CCM & DCM.

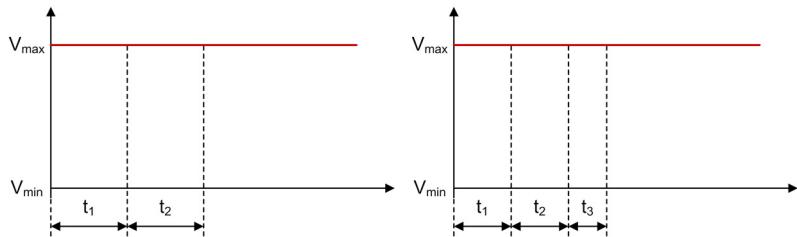


Figure 11.7.1. Active Clamp Forward - Clamping Capacitor  $C_1$  Voltage Waveforms in CCM and DCM

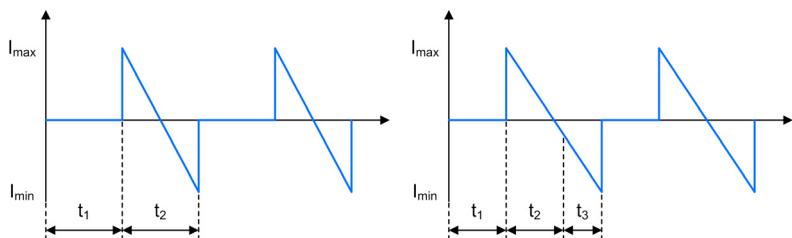


Figure 11.7.2. Active Clamp Forward - Clamping Capacitor  $C_1$  Current Waveforms in CCM and DCM

Average Clamping Capacitor Current:  $I_{C_1,avg} = 0A$

Clamping Capacitor Current during  $t_1$ :  $I_{C_1,t_1} = 0A$

Min. Clamping Capacitor Current during  $t_{2/3}$ :  $I_{C_1,min} = I_{Q_2,min}$

Max. Clamping Capacitor Current during  $t_{2/3}$ :  $I_{C_1,max} = I_{Q_2,max}$

Clamping Capacitor Voltage:  $V_{C_1} = V_{clamp}$

## 11.8. Rectifier Diode $D_1$

### 11.8.1. CCM & DCM.

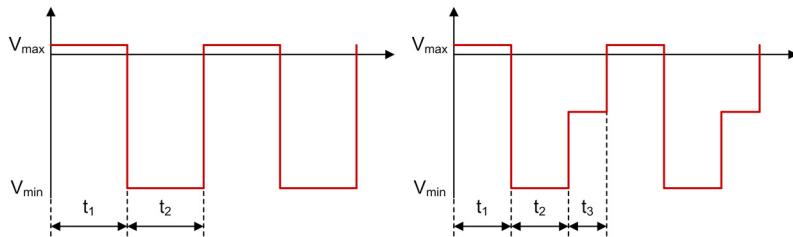


Figure 11.8.1. Active Clamp Forward - Rectifier Diode  $D_1$  Voltage Waveforms in CCM and DCM

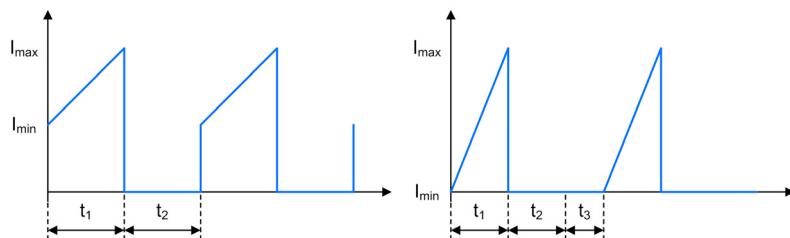


Figure 11.8.2. Active Clamp Forward - Rectifier Diode  $D_1$  Current Waveforms in CCM and DCM

Average Rectifier Diode Current:  $I_{D1,avg} = \frac{I_{N_s,min} + I_{N_s,max}}{2} \cdot t_2 \cdot f_{switch}$

Min. Rectifier Diode Current:  $I_{D1,min} = I_{trans,sec,min}$

Max. Rectifier Diode Current:  $I_{D1,max} = I_{trans,sec,max}$

Min. Rectifier Diode Voltage:  $V_{D1,min} = -V_{clamp} \cdot \frac{n_s}{n_p} + V_f$

Max. Rectifier Diode Voltage:  $V_{D1,max} = V_f$

Rectifier Diode Voltage during  $t_3$ :  $V_{D1,t_3} = -V_{out}$

## 11.9. Freewheeling Diode $D_2$

### 11.9.1. CCM & DCM.

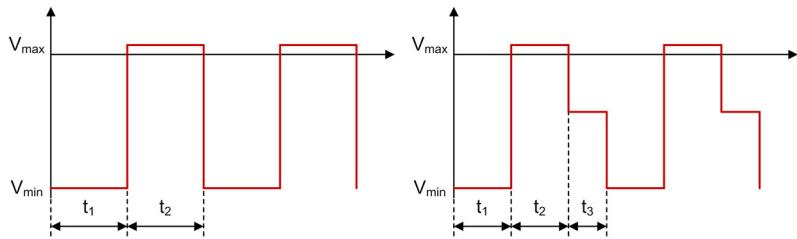


Figure 11.9.1. Active Clamp Forward - Freewheeling Diode  $D_2$  Voltage Waveforms in CCM and DCM

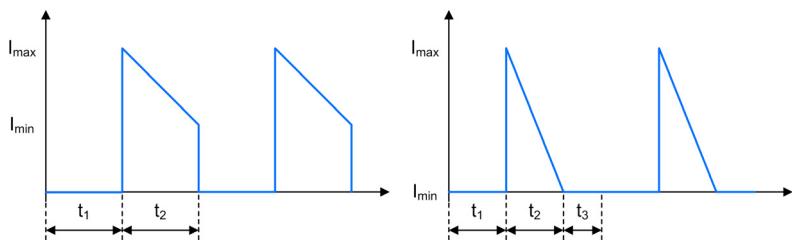


Figure 11.9.2. Active Clamp Forward - Freewheeling Diode  $D_2$  Current Waveforms in CCM and DCM

Average Freewheeling Diode Current:  $I_{D_2,avg} = I_{N_s,avg}$

Min. Freewheeling Diode Current:  $I_{D_2,min} = I_{N_s,min}$

Max. Freewheeling Diode Current:  $I_{D_2,max} = I_{N_s,max}$

Min. Freewheeling Diode Voltage:  $V_{D_2,min} = -V_{in} \cdot \frac{n_s}{n_p} + V_f$

Max. Freewheeling Diode Voltage:  $V_{D_2,max} = V_f$

Freewheeling Diode Voltage during  $t_3$ :  $V_{D_2,t_3} = -V_{clamp} \cdot \frac{n_s}{n_p} - V_{out}$

### 11.10. Input Capacitor $C_i$

#### 11.10.1. CCM & DCM.

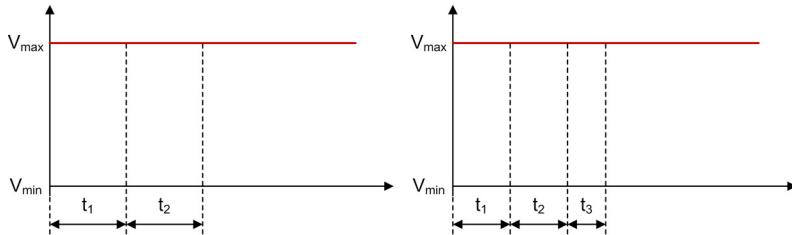


Figure 11.10.1. Active Clamp Forward - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

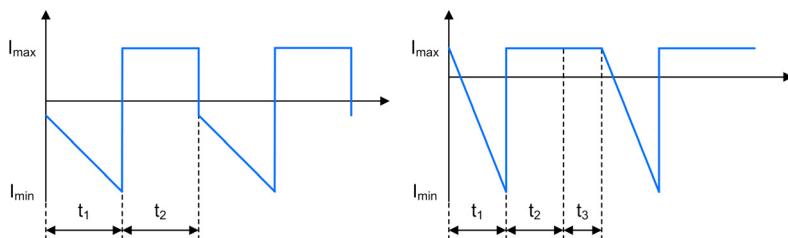


Figure 11.10.2. Active Clamp Forward - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current during } t_1: \quad I_{C_i,min,t_1} = I_{N_p,avg} - I_{trans,pri,max}$$

$$\text{Max. Input Capacitor Current during } t_1: \quad I_{C_i,max,t_1} = I_{N_p,avg} - I_{trans,pri,min}$$

$$\text{Input Capacitor Current during } t_2 \text{ and } t_3: \quad I_{C_i,t_2/3} = I_{N_p,avg}$$

$$\text{Average Input Capacitor Current:} \quad I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage:} \quad V_{C_i} = V_{in}$$

## 11.11. Output Capacitor $C_o$

### 11.11.1. CCM & DCM.

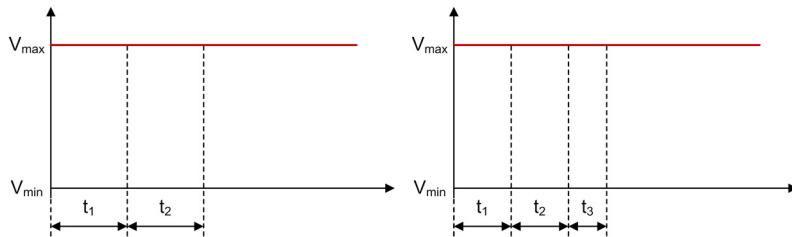


Figure 11.11.1. Active Clamp Forward - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

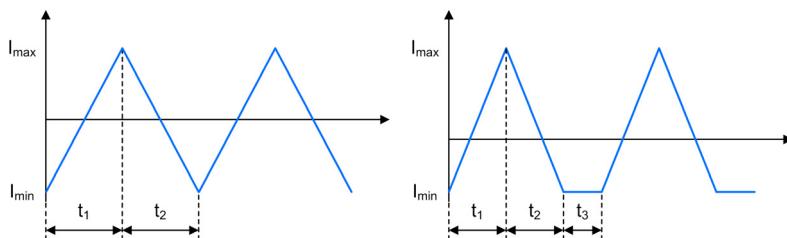


Figure 11.11.2. Active Clamp Forward - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

$$\text{Min. Output Capacitor Current: } I_{C_o,min} = I_{L_1,min} - I_{out}$$

$$\text{Max. Output Capacitor Current: } I_{C_o,max} = I_{L_1,max} - I_{out}$$

$$\text{Output Capacitor Current during } t_3: \quad I_{C_o,t_3} = I_{L_1,min} - I_{out}$$

$$\text{Average Output Capacitor Current: } I_{C_o,avg} = 0A$$

$$\text{Output Capacitor Voltage: } V_{C_o} = V_{out}$$



# Single Switch Forward Converter

A Single Switch Forward regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FET is conducting. The turns ratio between  $N_p$  and  $N_d$  is assumed to be 1:1.

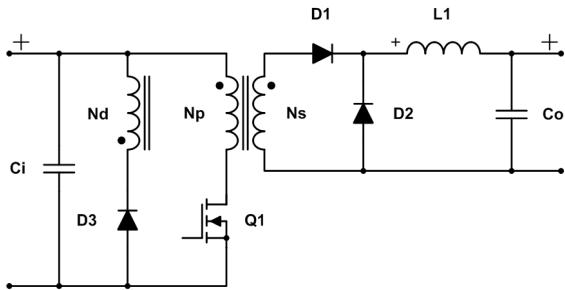


Figure 12.0.1. Schematic of a Single Switch Forward converter

## 12.1. General

$$\text{Secondary Side Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot \left( V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out} \right) \cdot t_1$$

### 12.1.1. Continuous Conduction Mode.

FET on, increasing current:  $t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out}+V_f}{V_{in} \cdot \frac{n_s}{n_p}}$

Demagnetization Time:  $t_d = t_1$

FET off, decreasing current:  $t_2 = \frac{1}{f_{switch}} - t_1$

Magnetization Current:  $I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,min} = I_{sec,min} \cdot \frac{n_s}{n_p}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

### 12.1.2. Discontinuous Conduction Mode.

FET on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot (V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

Demagnetization Time:  $t_d = t_1$

FET off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in} \cdot \frac{n_s}{n_p}}{(V_{out}+V_f)} - t_1$

FET off, no current (if  $t_2 > t_d$ ):  $t_3 = \frac{1}{f_{switch}} - t_1 - t_2$

FET off, no current (if  $t_d \geq t_2$ ):  $t_3 = \frac{1}{f_{switch}} - t_1 - t_d$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{ripple}$

Min. Primary Current:  $I_{pri,min} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

### 12.2. Primary Side Transformer Winding $N_p$

#### 12.2.1. CCM & DCM.

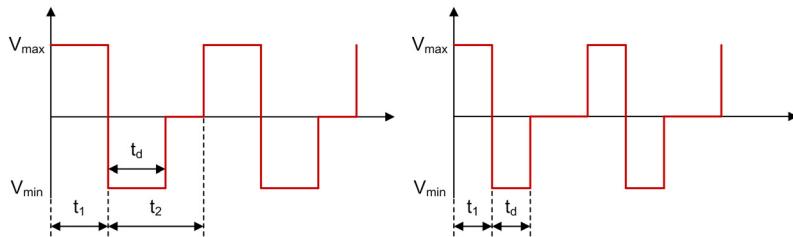


Figure 12.2.1. Single Switch Forward - Primary Side Transformer Winding  $N_p$  Voltage Waveforms in CCM and DCM

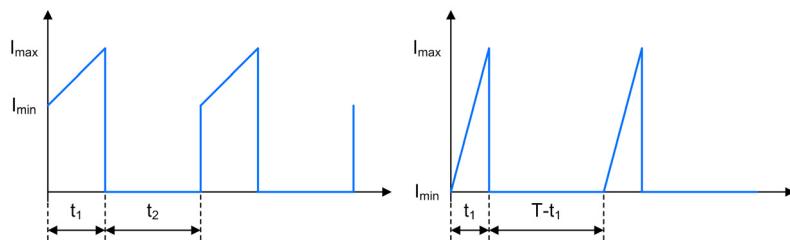


Figure 12.2.2. Single Switch Forward - Primary Side Transformer Winding  $N_p$  Current Waveforms in CCM and DCM

Average Primary Transformer Current:  $I_{N_p,avg} = \left( \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \right) \cdot f_{switch}$

Min. Primary Transformer Current:  $I_{N_p,min} = I_{pri,min}$

Max. Primary Transformer Current:  $I_{N_p,max} = I_{pri,max}$

Min. Primary Transformer Voltage:  $V_{N_p,min} = -V_{in}$

Max. Primary Transformer Voltage:  $V_{N_p,max} = V_{in}$

Primary Transformer Voltage after  $t_d$ :  $V_{N_p,t_{ad}} = 0V$

Primary Transformer Voltage during  $t_3$ :  $V_{N_p,t_3} = 0V$

## 12.3. Secondary Side Transformer Winding $N_s$

### 12.3.1. CCM & DCM.

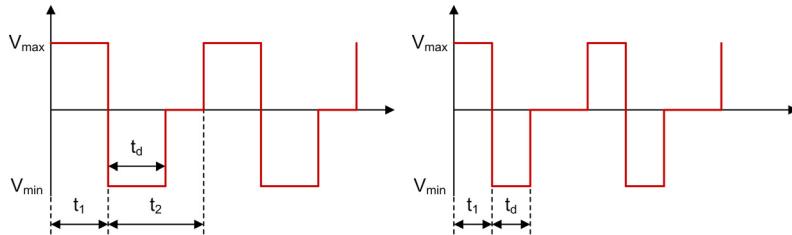


Figure 12.3.1. Single Switch Forward - Secondary Side Transformer Winding  $N_s$  Voltage Waveforms in CCM and DCM

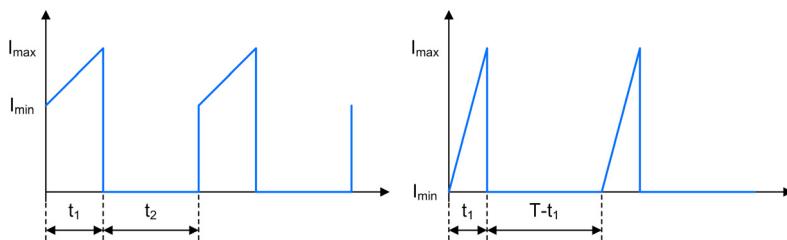


Figure 12.3.2. Single Switch Forward - Secondary Side Transformer Winding  $N_s$  Current Waveforms in CCM and DCM

Average Secondary Transformer Current:  $I_{N_s,avg} = \frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 \cdot f_{switch}$

Min. Secondary Transformer Current:  $I_{N_s,min} = I_{sec,min}$

Max. Secondary Transformer Current:  $I_{N_s,max} = I_{sec,max}$

Min. Secondary Transformer Voltage:  $V_{N_s,min} = -V_{in} \cdot \frac{n_s}{n_p} - V_f$

Max. Secondary Transformer Voltage:  $V_{N_s,max} = V_{in} \cdot \frac{n_s}{n_p}$

Secondary Transformer Voltage after  $t_d$ :  $V_{N_s,t_{ad}} = 0V$

Secondary Transformer Voltage during  $t_3$ :  $V_{N_s,t_3} = 0V$

## 12.4. Inductor $L_1$

### 12.4.1. CCM & DCM.

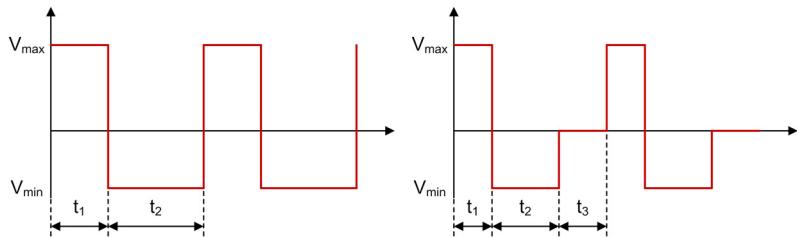


Figure 12.4.1. Single Switch Forward - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

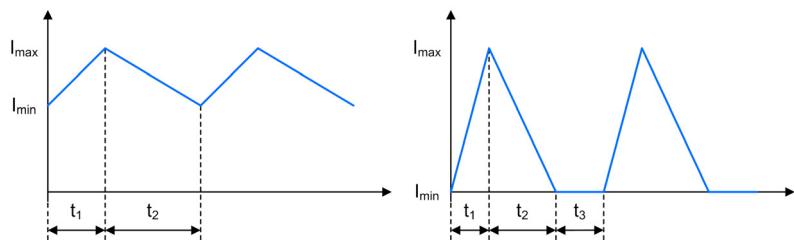


Figure 12.4.2. Single Switch Forward - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:  $I_{L_1,avg} = \frac{I_{sec,max} + I_{sec,min}}{2} \cdot (t_1 + t_2) \cdot f_{switch}$

Min. Inductor Current:  $I_{L_1,min} = I_{sec,min}$

Max. Inductor Current:  $I_{L_1,max} = I_{sec,max}$

Min. Inductor Voltage:  $V_{L_1,min} = -V_{out} - V_f$

Max. Inductor Voltage:  $V_{L_1,max} = V_{in} \cdot \frac{n_s}{n_p} - V_{out} - V_f$

Inductor Voltage during  $t_3$ :  $V_{L_1,t_3} = 0V$

## 12.5. FET $Q_1$

### 12.5.1. CCM & DCM.

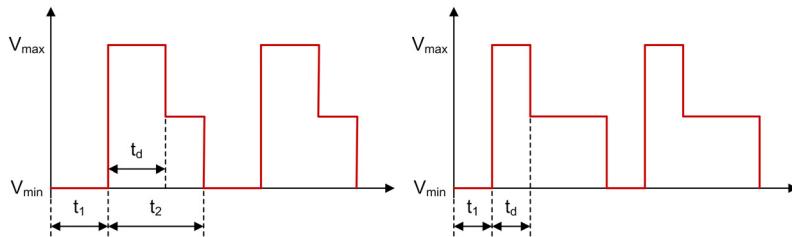


Figure 12.5.1. Single Switch Forward - FET  $Q_1$  Voltage Waveforms in CCM and DCM

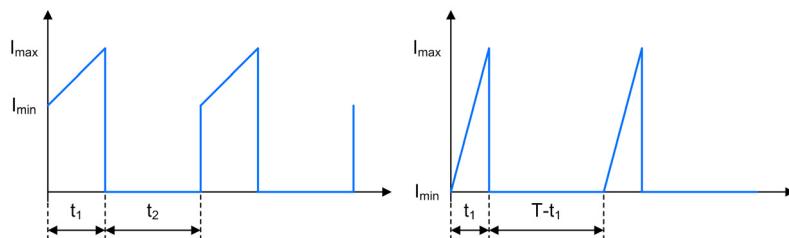


Figure 12.5.2. Single Switch Forward - FET  $Q_1$  Current Waveforms in CCM and DCM

Average FET Current:  $I_{Q_1,avg} = I_{N_p,avg}$

Min. FET Current:  $I_{Q_1,min} = I_{pri,min}$

Max. FET Current:  $I_{Q_1,max} = I_{pri,max}$

Min. FET Voltage:  $V_{Q_1,min} = 0V$

Max. FET Voltage:  $V_{Q_1,max} = 2 \cdot V_{in} + V_f$

FET Voltage after  $t_d$ :  $V_{Q_1,t_{ad}} = V_{in}$

FET Voltage during  $t_3$ :  $V_{Q_1,t_3} = V_{in}$

### 12.6. Demagnetization Winding $N_d$

#### 12.6.1. CCM & DCM.

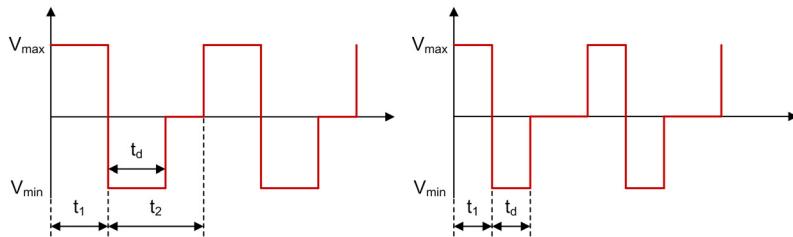


Figure 12.6.1. Single Switch Forward - Demagnetization Winding  $N_d$  Voltage Waveforms in CCM and DCM

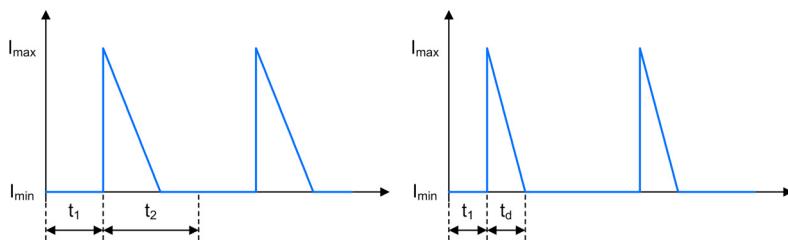


Figure 12.6.2. Single Switch Forward - Demagnetization Winding  $N_d$  Current Waveforms in CCM and DCM

$$\text{Average Demagnetization Winding Current: } I_{N_d,\text{avg}} = \frac{I_{mag}}{2} \cdot t_d \cdot f_{switch}$$

$$\text{Min. Demagnetization Winding Current: } I_{N_d,\text{min}} = 0A$$

$$\text{Max. Demagnetization Winding Current: } I_{N_d,\text{max}} = I_{mag}$$

$$\text{Min. Demagnetization Winding Voltage: } V_{N_d,\text{min}} = -V_{in}$$

$$\text{Max. Demagnetization Winding Voltage: } V_{N_d,\text{max}} = V_f$$

$$\text{Demagnetization Winding Voltage after } t_d: V_{N_d,t_{ad}} = 0V$$

$$\text{Demagnetization Winding Voltage during } t_3: V_{N_d,t_3} = 0V$$

## 12.7. Demagnetization Diode $D_3$

### 12.7.1. CCM & DCM.

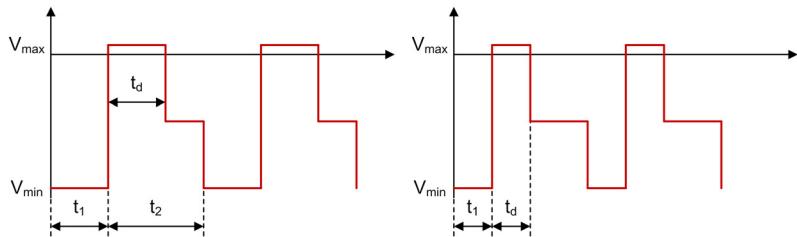


Figure 12.7.1. Single Switch Forward - Demagnetization Diode  $D_3$  Voltage Waveforms in CCM and DCM

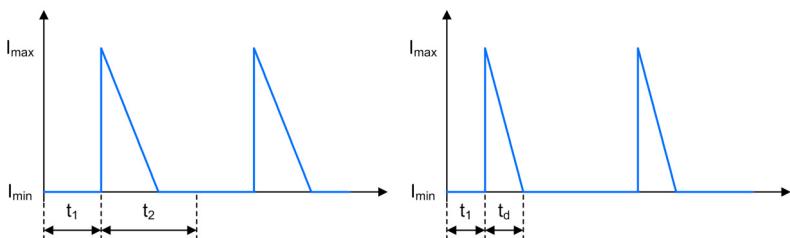


Figure 12.7.2. Single Switch Forward - Demagnetization Diode  $D_3$  Current Waveforms in CCM and DCM

Average Demagnetization Diode Current:  $I_{D3,avg} = \frac{I_{mag}}{2} \cdot t_d \cdot f_{switch}$

Min. Demagnetization Diode Current:  $I_{D3,min} = 0A$

Max. Demagnetization Diode Current:  $I_{D3,max} = I_{mag}$

Min. Demagnetization Diode Voltage:  $V_{D3,min} = -2 \cdot V_{in}$

Max. Demagnetization Diode Voltage:  $V_{D3,max} = V_f$

Demagnetization Diode Voltage after  $t_d$ :  $V_{D3,t_{ad}} = -V_{in}$

Demagnetization Diode Voltage during  $t_3$ :  $V_{D3,t_3} = -V_{in}$

## 12.8. Rectifier Diode $D_1$

### 12.8.1. CCM & DCM.

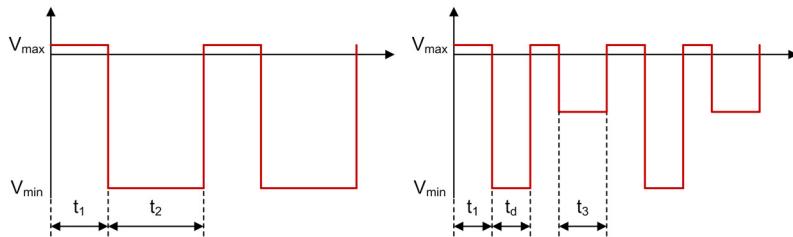


Figure 12.8.1. Single Switch Forward - Rectifier Diode  $D_1$  Voltage Waveforms in CCM and DCM

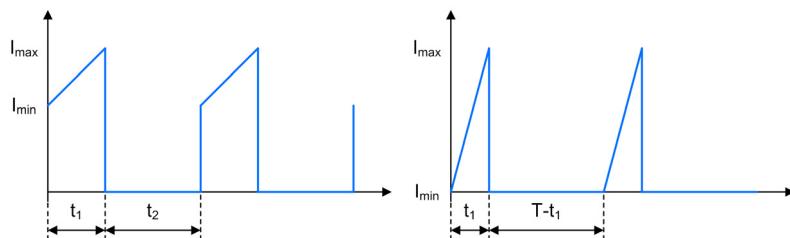


Figure 12.8.2. Single Switch Forward - Rectifier Diode  $D_1$  Current Waveforms in CCM and DCM

$$\text{Average Rectifier Diode Current: } I_{D_1,\text{avg}} = \frac{I_{\text{sec,min}} + I_{\text{sec,max}}}{2} \cdot t_2 \cdot f_{\text{switch}}$$

$$\text{Min. Rectifier Diode Current: } I_{D_1,\text{min}} = I_{\text{trans,sec,min}}$$

$$\text{Max. Rectifier Diode Current: } I_{D_1,\text{max}} = I_{\text{trans,sec,max}}$$

$$\text{Min. Rectifier Diode Voltage: } V_{D_1,\text{min}} = -(V_{in} + V_f) \cdot \frac{n_s}{n_p} + V_f$$

$$\text{Max. Rectifier Diode Voltage: } V_{D_1,\text{max}} = V_f$$

$$\text{Rectifier Diode Voltage after } t_d: \quad V_{D_1,t_{ad}} = V_f$$

$$\text{Rectifier Diode Voltage during } t_3: \quad V_{D_1,t_3} = -V_{out}$$

## 12.9. Freewheeling Diode $D_2$

### 12.8.1. CCM & DCM.

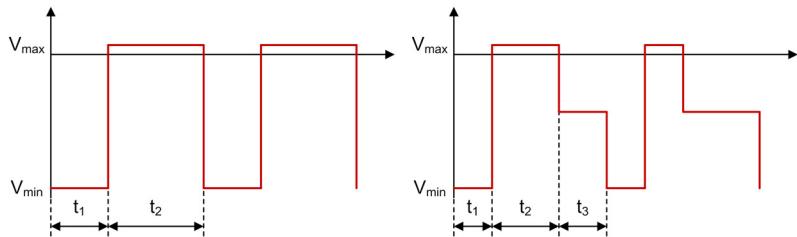


Figure 12.9.1. Single Switch Forward - Freewheeling Diode  $D_2$  Voltage Waveforms in CCM and DCM

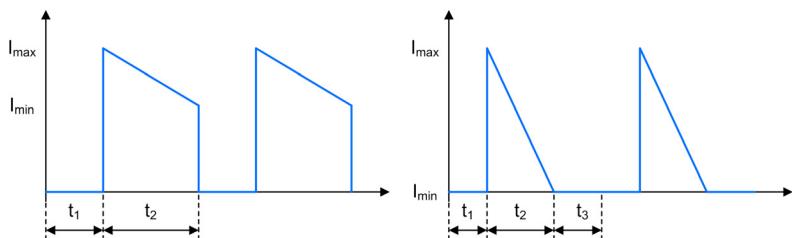


Figure 12.9.2. Single Switch Forward - Freewheeling Diode  $D_2$  Current Waveforms in CCM and DCM

Average Freewheeling Diode Current:  $I_{D_2,\text{avg}} = I_{N_s,\text{avg}}$

Min. Freewheeling Diode Current:  $I_{D_2,\text{min}} = I_{\text{sec,min}}$

Max. Freewheeling Diode Current:  $I_{D_2,\text{max}} = I_{\text{sec,max}}$

Min. Freewheeling Diode Voltage:  $V_{D_2,\text{min}} = -V_{in} \cdot \frac{n_s}{n_p} + V_f$

Max. Freewheeling Diode Voltage:  $V_{D_2,\text{max}} = V_f$

Freewheeling Diode Voltage during  $t_3$ :  $V_{D_2,t_3} = -V_{out}$

## 12.10. Input Capacitor $C_i$

### 12.10.1. CCM & DCM.

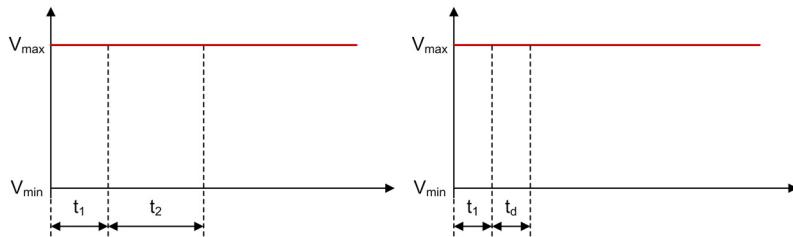


Figure 12.10.1. Single Switch Forward - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

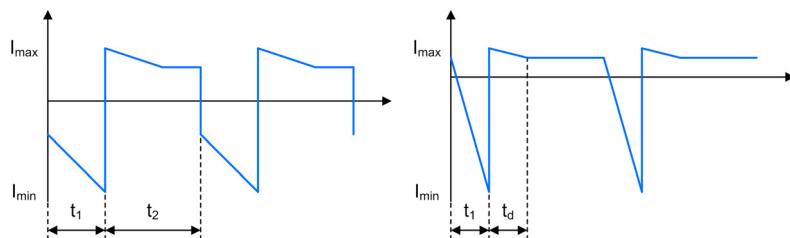


Figure 12.10.2. Single Switch Forward - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current during } t_1: \quad I_{C_i,min,t_1} = I_{N_p,avg} - I_{pri,max} - I_{D3,avg}$$

$$\text{Max. Input Capacitor Current during } t_1: \quad I_{C_i,max,t_1} = I_{N_p,avg} - I_{pri,min} - I_{D3,avg}$$

$$\text{Min. Input Capacitor Current during } t_d: \quad I_{C_i,min,t_d} = I_{N_p,avg} - I_{D3,avg}$$

$$\text{Max. Input Capacitor Current during } t_d: \quad I_{C_i,max,t_d} = I_{N_p,avg} - I_{D3,avg} + I_{mag}$$

$$\text{Input Capacitor Current after } t_d: \quad I_{C_i,t_{ad}} = I_{N_p,avg} - I_{D3,avg}$$

$$\text{Input Capacitor Current during } t_3: \quad I_{C_i,t_3} = I_{N_p,avg} - I_{D3,avg}$$

$$\text{Average Input Capacitor Current:} \quad I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage:} \quad V_{C_i} = V_{in}$$

## 12.11. Output Capacitor $C_o$

### 12.11.1. CCM & DCM.

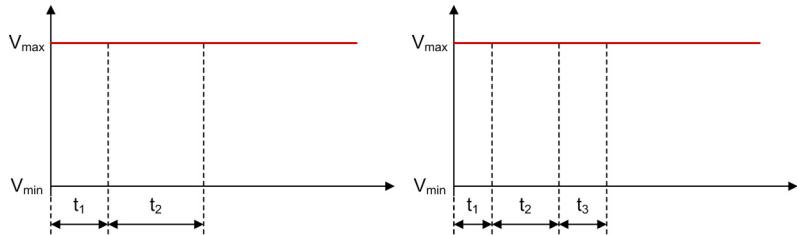


Figure 12.11.1. Single Switch Forward - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

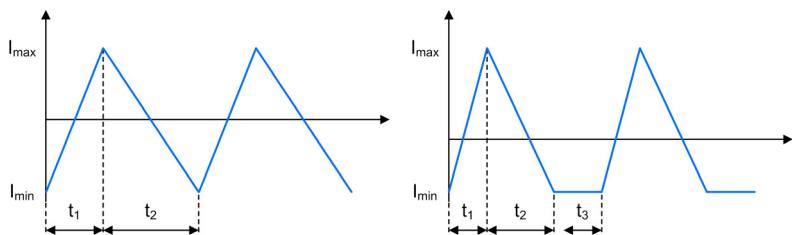


Figure 12.11.2. Single Switch Forward - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

$$\text{Min. Output Capacitor Current: } I_{C_o,min} = I_{L_1,min} - I_{out}$$

$$\text{Max. Output Capacitor Current: } I_{C_o,max} = I_{L_1,max} - I_{out}$$

$$\text{Average Output Capacitor Current: } I_{C_o,avg} = 0A$$

$$\text{Output Capacitor Voltage: } V_{C_o} = V_{out}$$



# Two Switch Forward Converter

A Two Switch Forward regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FETs are conducting.

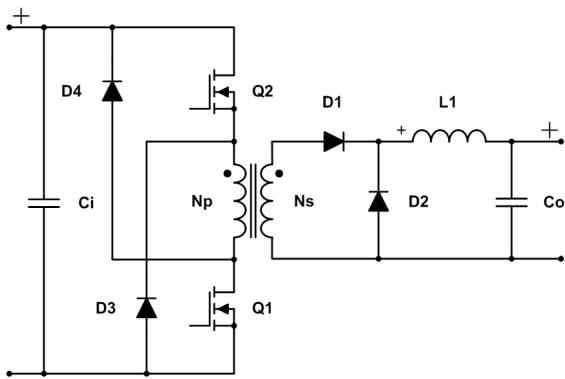


Figure 13.0.1. Schematic of a Two Switch Forward converter

### 13.1. General

$$\text{Secondary Side Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot \left( V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out} \right) \cdot t_1$$

### 13.1.1. Continuous Conduction Mode.

FETs on, increasing current:  $t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out}+V_f}{V_{in} \cdot \frac{n_s}{n_p}}$

Demagnetization Time:  $t_d = t_1$

FETs off, decreasing current:  $t_2 = \frac{1}{f_{switch}} - t_1$

Magnetization Current:  $I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,max} = I_{sec,min} \cdot \frac{n_s}{n_p}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

### 13.1.2. Discontinuous Conduction Mode.

FETs on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot (V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

Demagnetization Time:  $t_d = t_1$

FETs off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in} \cdot \frac{n_s}{n_p}}{(V_{out}+V_f)} - t_1$

FETs off, no current (if  $t_2 > t_d$ ):  $t_3 = \frac{1}{f_{switch}} - t_1 - t_2$

FETs off, no current (if  $t_d \geq t_2$ ):  $t_3 = \frac{1}{f_{switch}} - t_1 - t_d$

Magnetization Current:  $I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{ripple}$

Min. Primary Current:  $I_{pri,max} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out}+V_f) \cdot I_{out}}{V_{in}}$

### 13.2. Primary Side Transformer Winding $N_p$

#### 13.2.1. CCM & DCM.

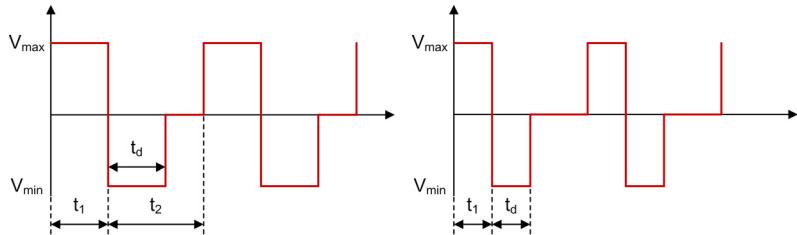


Figure 13.2.1. Two Switch Forward - Primary Side Transformer Winding  $N_p$  Voltage Waveforms in CCM and DCM

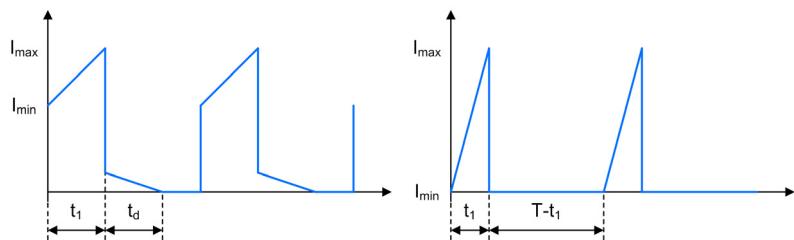


Figure 13.2.2. Two Switch Forward - Primary Side Transformer Winding  $N_p$  Current Waveforms in CCM and DCM

$$\text{Average Primary Transformer Current: } I_{N_p,\text{avg}} = \left( \frac{I_{\text{pri},\text{min}} + I_{\text{pri},\text{max}}}{2} \cdot t_1 + \frac{I_{\text{mag}}}{2} \cdot t_d \right) \cdot f_{\text{switch}}$$

$$\text{Min. Primary Transformer Current during } t_1: \quad I_{N_p,\text{min},t_1} = I_{\text{pri},\text{min}}$$

$$\text{Max. Primary Transformer Current during } t_1: \quad I_{N_p,\text{max},t_1} = I_{\text{pri},\text{max}}$$

$$\text{Min. Primary Transformer Current during } t_2: \quad I_{N_p,\text{min},t_2} = 0V$$

$$\text{Max. Primary Transformer Current during } t_2: \quad I_{N_p,\text{max},t_2} = I_{\text{mag}}$$

$$\text{Min. Primary Transformer Voltage: } V_{N_p,\text{min}} = -V_{in} - 2 \cdot V_f$$

$$\text{Max. Primary Transformer Voltage: } V_{N_p,\text{max}} = V_{in}$$

$$\text{Primary Transformer Voltage after } t_d: \quad V_{N_p,t_{ad}} = 0V$$

$$\text{Primary Transformer Voltage during } t_3: \quad V_{N_p,t_3} = 0V$$

### 13.3. Secondary Side Transformer Winding $N_s$

#### 13.3.1. CCM & DCM.

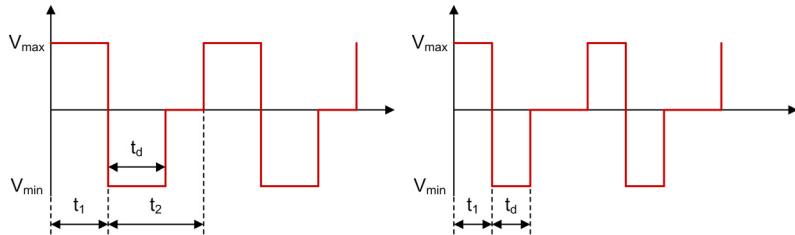


Figure 13.3.1. Two Switch Forward - Secondary Side Transformer Winding  $N_s$  Voltage Waveforms in CCM and DCM

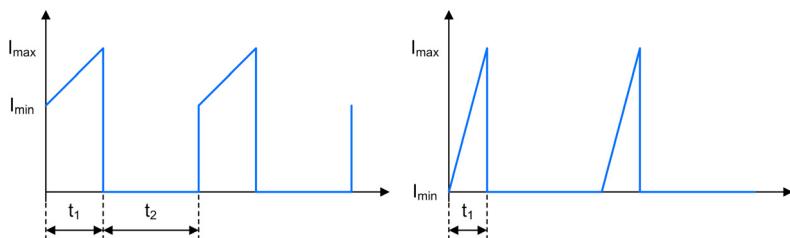


Figure 13.3.2. Two Switch Forward - Secondary Side Transformer Winding  $N_s$  Current Waveforms in CCM and DCM

Average Secondary Transformer Current:  $I_{N_s,avg} = \frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 \cdot f_{switch}$

Min. Secondary Transformer Current:  $I_{N_s,min} = I_{sec,min}$

Max. Secondary Transformer Current:  $I_{N_s,max} = I_{sec,max}$

Min. Secondary Transformer Voltage:  $V_{N_s,min} = -(V_{in} + 2 \cdot V_f) \cdot \frac{n_s}{n_p}$

Max. Secondary Transformer Voltage:  $V_{N_s,max} = V_{in} \cdot \frac{n_s}{n_p}$

Secondary Transformer Voltage after  $t_d$ :  $V_{N_s,t_{ad}} = 0V$

Secondary Transformer Voltage during  $t_3$ :  $V_{N_s,t_3} = 0V$

### 13.4. Inductor $L_1$

#### 13.4.1. CCM & DCM.

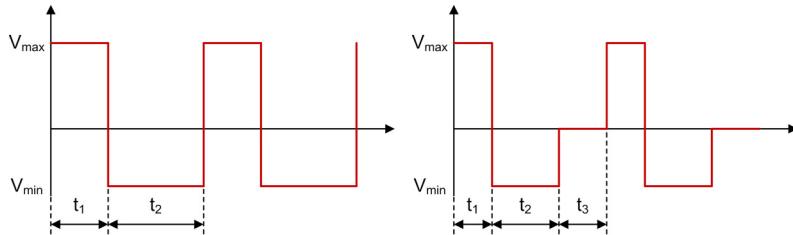


Figure 13.4.1. Two Switch Forward - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

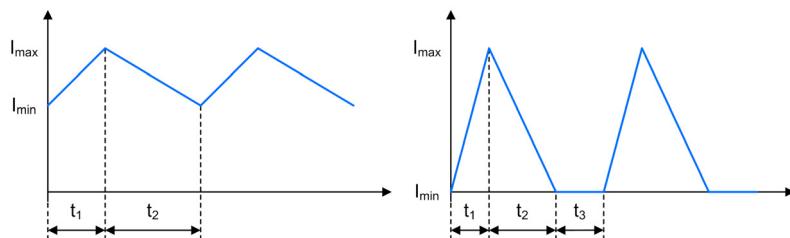


Figure 13.4.2. Two Switch Forward - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:  $I_{ind,avg} = \frac{I_{sec,max} + I_{sec,min}}{2} \cdot (t_1 + t_2) \cdot f_{switch}$

Min. Inductor Current:  $I_{ind,min} = I_{trans,sec,min}$

Max. Inductor Current:  $I_{ind,max} = I_{trans,sec,max}$

Min. Inductor Voltage:  $V_{ind,min} = -V_{out} - V_f$

Max. Inductor Voltage:  $V_{ind,max} = V_{in} \cdot \frac{n_s}{n_p} - V_{out} - V_f$

Inductor Voltage during  $t_3$ :  $V_{ind,t_3} = 0V$

### 13.5. FET $Q_1/Q_2$

#### 13.5.1. CCM & DCM.

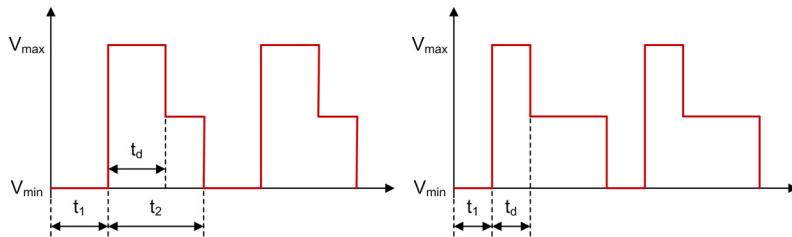


Figure 13.5.1. Two Switch Forward - FET  $Q_1/Q_2$  Voltage Waveforms in CCM and DCM

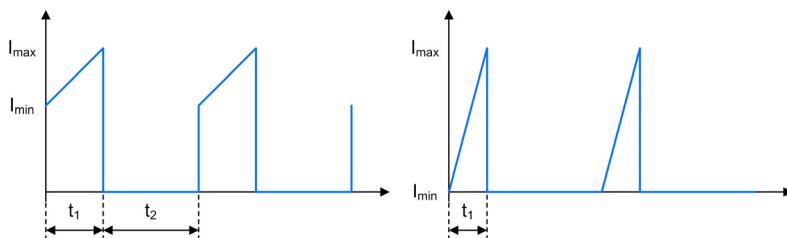


Figure 13.5.2. Two Switch Forward - FET  $Q_1/Q_2$  Current Waveforms in CCM and DCM

Average FET Current:  $I_{Q_{1/2},avg} = I_{N_p,avg}$

Min. FET Current:  $I_{Q_{1/2},min} = I_{pri,min}$

Max. FET Current:  $I_{Q_{1/2},max} = I_{pri,max}$

Min. FET Voltage:  $V_{Q_{1/2},min} = 0V$

Max. FET Voltage:  $V_{Q_{1/2},max} = V_{in} + V_f$

FET Voltage after  $t_d$ :  $V_{Q_1,t_{ad}} = \frac{1}{2} \cdot V_{in}$

FET Voltage during  $t_3$ :  $V_{Q_{1/2},t_3} = \frac{1}{2} \cdot V_{in}$

### 13.6. Demagnetization Diode $D_3/D_4$

#### 13.6.1. CCM & DCM.

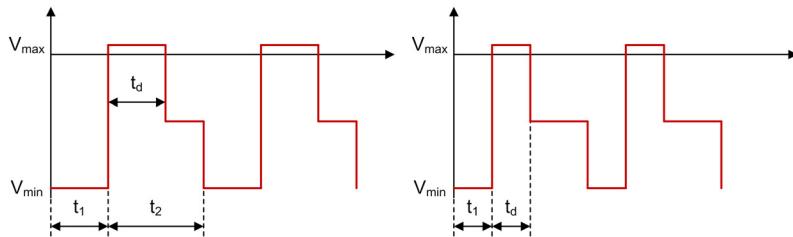


Figure 13.6.1. Two Switch Forward - Demagnetization Diode  $D_3/D_4$  Voltage Waveforms in CCM and DCM

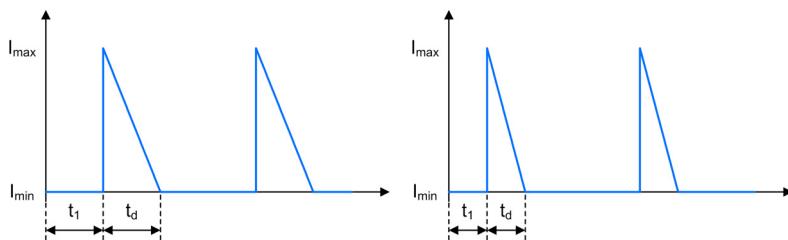


Figure 13.6.2. Two Switch Forward - Demagnetization Diode  $D_3/D_4$  Current Waveforms in CCM and DCM

Average Demagnetization Diode Current:  $I_{D_{3/4},avg} = \frac{I_{mag}}{2} \cdot t_d \cdot f_{switch}$

Min. Demagnetization Diode Current:  $I_{D_{3/4},min} = 0A$

Max. Demagnetization Diode Current:  $I_{D_{3/4},max} = I_{mag}$

Min. Demagnetization Diode Voltage:  $V_{D_{3/4},min} = -V_{in}$

Max. Demagnetization Diode Voltage:  $V_{D_{3/4},max} = V_f$

Demagnetization Diode Voltage after  $t_d$ :  $V_{D_{3/4},t_{ad}} = -\frac{1}{2} \cdot V_{in}$

Demagnetization Diode Voltage during  $t_3$ :  $V_{D_{3/4},t_3} = -\frac{1}{2} \cdot V_{in}$

### 13.7. Rectifier Diode $D_1$

#### 13.7.1. CCM & DCM.

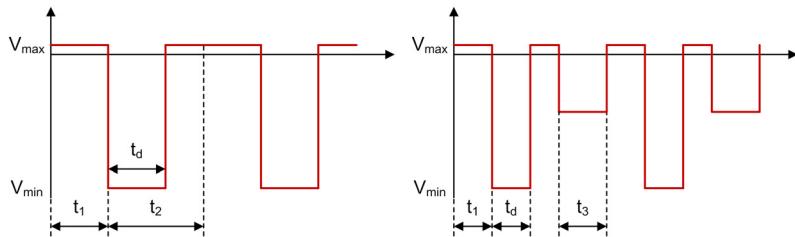


Figure 13.7.1. Two Switch Forward - Rectifier Diode  $D_1$  Voltage Waveforms in CCM and DCM

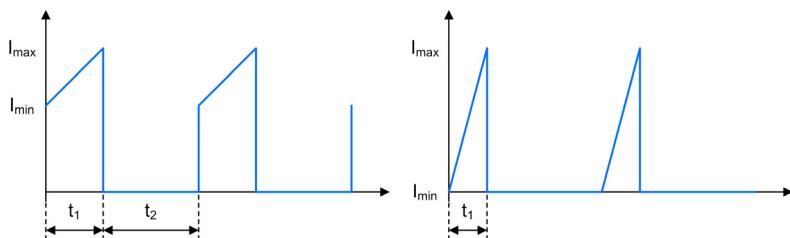


Figure 13.7.2. Two Switch Forward - Rectifier Diode  $D_1$  Current Waveforms in CCM and DCM

$$\text{Average Rectifier Diode Current: } I_{D_1,\text{avg}} = \frac{I_{N_s,\text{min}} + I_{N_s,\text{max}}}{2} \cdot t_2 \cdot f_{\text{switch}}$$

$$\text{Min. Rectifier Diode Current: } I_{D_1,\text{min}} = I_{N_s,\text{min}}$$

$$\text{Max. Rectifier Diode Current: } I_{D_1,\text{max}} = I_{N_s,\text{max}}$$

$$\text{Min. Rectifier Diode Voltage: } V_{D_1,\text{min}} = -(V_{in} + 2 \cdot V_f) \cdot \frac{n_s}{n_p} + V_f$$

$$\text{Max. Rectifier Diode Voltage: } V_{D_1,\text{max}} = V_f$$

$$\text{Rectifier Diode Voltage after } t_d: V_{D_1,t_{ad}} = V_f$$

$$\text{Rectifier Diode Voltage during } t_3: V_{D_1,t_3} = -V_{out}$$

### 13.8. Freewheeling Diode $D_2$

#### 13.8.1. CCM & DCM.

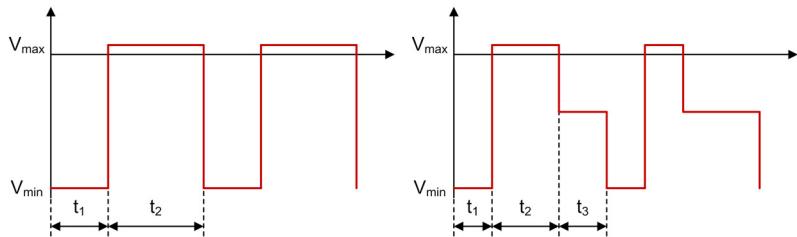


Figure 13.8.1. Two Switch Forward - Freewheeling Diode  $D_2$  Voltage Waveforms in CCM and DCM

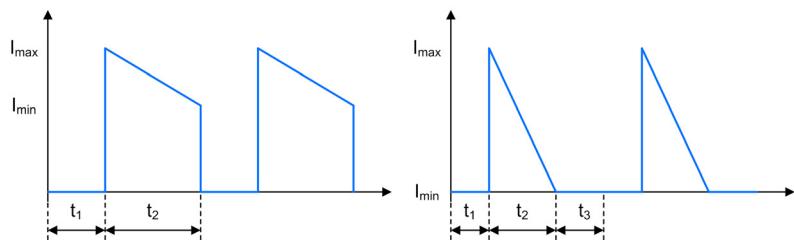


Figure 13.8.2. Two Switch Forward - Freewheeling Diode  $D_2$  Current Waveforms in CCM and DCM

Average Freewheeling Diode Current:  $I_{D_2,avg} = I_{N_s,avg}$

Min. Freewheeling Diode Current:  $I_{D_2,min} = I_{N_s,min}$

Max. Freewheeling Diode Current:  $I_{D_2,max} = I_{N_s,max}$

Min. Freewheeling Diode Voltage:  $V_{D_2,min} = -V_{in} \cdot \frac{n_s}{n_p} + V_f$

Max. Freewheeling Diode Voltage:  $V_{D_2,max} = V_f$

Freewheeling Diode Voltage during  $t_3$ :  $V_{D_2,t_3} = -V_{out}$

### 13.9. Input Capacitor $C_i$

#### 13.9.1. CCM & DCM.

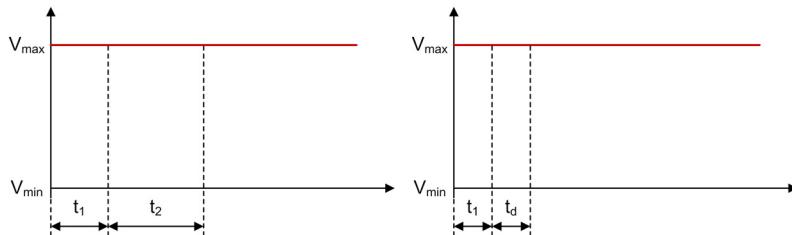


Figure 13.9.1. Two Switch Forward - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

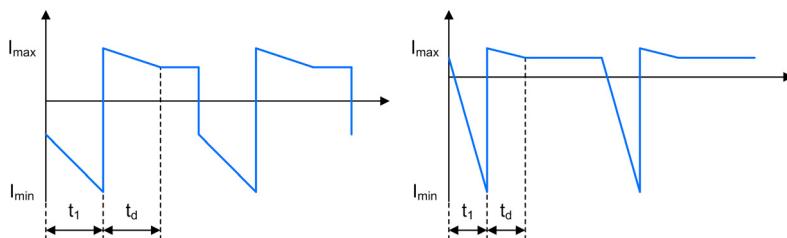


Figure 13.9.2. Two Switch Forward - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

Min. Input Capacitor Current during  $t_1$ :  $I_{C_i,min,t_1} = I_{N_p,avg} - I_{N_p,max} - I_{D_{3/4},avg}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_i,max,t_1} = I_{N_p,avg} - I_{N_p,min} - I_{D_{3/4},avg}$

Min. Input Capacitor Current during  $t_d$ :  $I_{C_i,min,t_{2/3}} = I_{N_p,avg} - I_{D_{3/4},avg}$

Max. Input Capacitor Current during  $t_d$ :  $I_{C_i,max,t_{2/3}} = I_{N_p,avg} - I_{D_{3/4},avg} + I_{mag}$

Input Capacitor Current after  $t_d$ :  $I_{C_i,t_{ad}} = I_{N_p,avg} - I_{D_{3/4},avg}$

Input Capacitor Current during  $t_3$ :  $I_{C_i,t_3} = I_{N_p,avg} - I_{D_{3/4},avg}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

### 13.10. Output Capacitor $C_o$

#### 13.10.1. CCM & DCM.

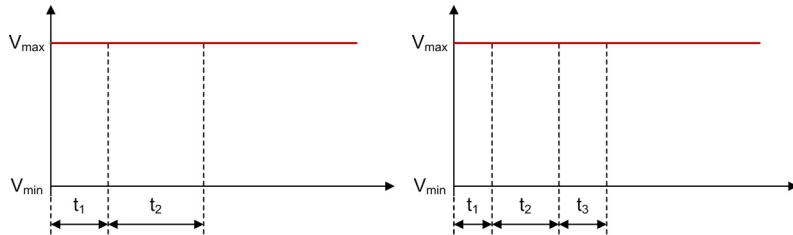


Figure 13.10.1. Two Switch Forward - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

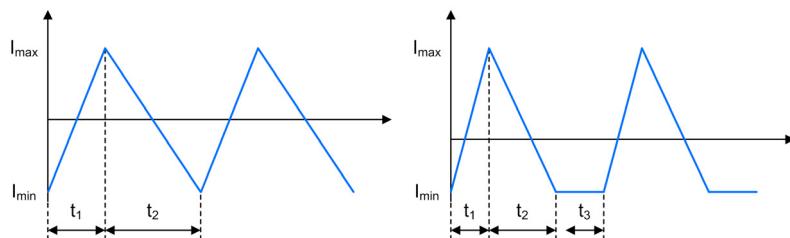


Figure 13.10.2. Two Switch Forward - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

$$\text{Min. Output Capacitor Current: } I_{C_o,min} = I_{L_1,min} - I_{out}$$

$$\text{Max. Output Capacitor Current: } I_{C_o,max} = I_{L_1,max} - I_{out}$$

$$\text{Average Output Capacitor Current: } I_{C_o,avg} = 0A$$

$$\text{Output Capacitor Voltage: } V_{C_o} = V_{out}$$

# Push-Pull Converter

A Push-Pull regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FETs are conducting.

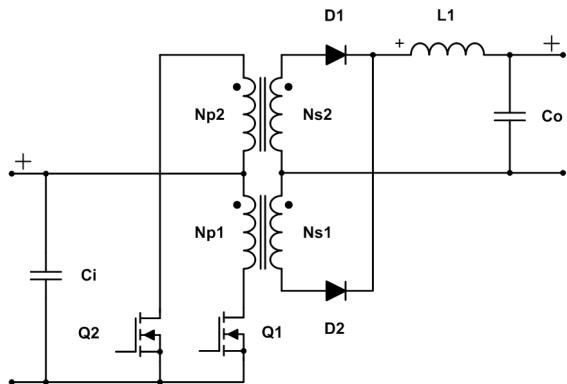


Figure 14.0.1. Schematic of a Push-Pull converter

## 14.1. General

$$\text{Secondary Side Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot (V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot t_1$$

$$\text{Magnetization Current: } I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$$

#### 14.1.1. Continuous Conduction Mode.

FET on, increasing current:  $t_1 = \frac{1}{2 \cdot f_{switch}} \cdot \frac{V_{out} + V_f}{V_{in} \cdot \frac{n_s}{n_p}}$

FET off, decreasing current:  $t_2 = \frac{1}{2 \cdot f_{switch}} - t_1$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,min} = I_{sec,min} \cdot \frac{n_s}{n_p} - \frac{1}{2} \cdot I_{mag}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

#### 14.1.2. Discontinuous Conduction Mode.

FET on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out} + V_f}{2 \cdot f_{switch} \cdot (V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

FET off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in} \cdot \frac{n_s}{n_p}}{(V_{out} + V_f)} - t_1$

FET off, demagnetization:  $t_3 = \frac{1}{2 \cdot f_{switch}} - t_1 - t_2$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{ripple}$

Min. Primary Current:  $I_{pri,max} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

## 14.2. Primary Side Transformer Windings $N_{p1}$ and $N_{p2}$

### 14.2.1. CCM.

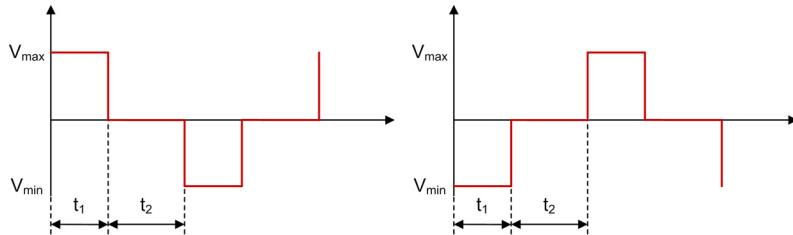


Figure 14.2.1. Push-Pull - Primary Side Transformer Windings  $N_{p1}$  and  $N_{p2}$  Voltage Waveforms in CCM

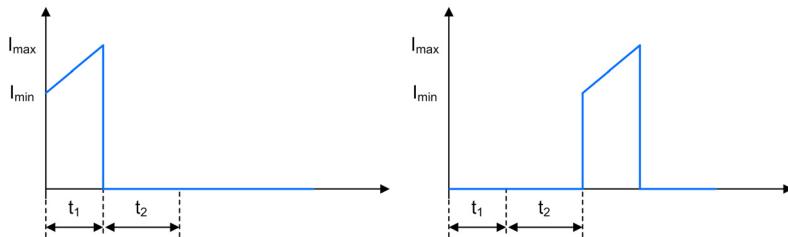


Figure 14.2.2. Push-Pull - Primary Side Transformer Windings  $N_{p1}$  and  $N_{p2}$  Current Waveforms in CCM

Average Primary Side Transformer Current:  $I_{N_{p1/p2},avg} = \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$

Min. Primary Side Transformer Current:  $I_{N_{p1/p2},min} = I_{pri,min}$

Max. Primary Side Transformer Current:  $I_{N_{p1/p2},max} = I_{pri,max}$

Min. Primary Side Transformer Voltage:  $V_{N_{p1/p2},min} = -V_{in}$

Max. Primary Side Transformer Voltage:  $V_{N_{p1/p2},max} = V_{in}$

### 14.2.2. DCM.

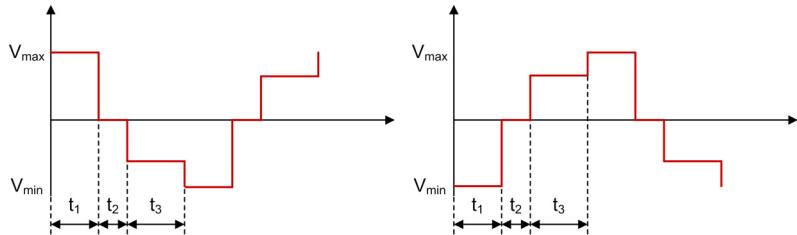


Figure 14.2.3. Push-Pull - Primary Side Transformer Windings  $N_{p1}$  and  $N_{p2}$  Voltage Waveforms in DCM

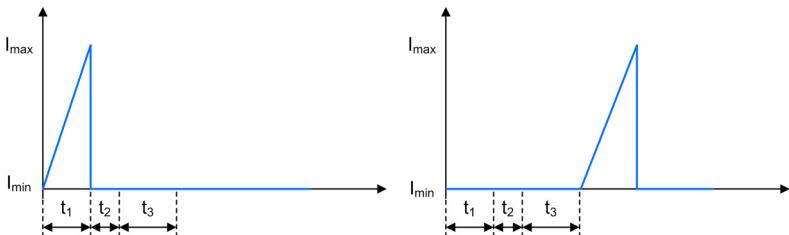


Figure 14.2.4. Push-Pull - Primary Side Transformer Windings  $N_{p1}$  and  $N_{p2}$  Current Waveforms in DCM

Average Primary Transformer Current:

$$I_{N_{p1/p2},avg} = \frac{I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$$

Min. Primary Transformer Current:

$$I_{N_{p1/p2},min} = I_{pri,min}$$

Max. Primary Transformer Current:

$$I_{N_{p1/p2},max} = I_{pri,max}$$

Min. Primary Transformer Voltage:

$$V_{N_{p1/p2},min} = -V_{in}$$

Max. Primary Transformer Voltage:

$$V_{N_{p1/p2},max} = V_{in}$$

Min. Primary Transformer Voltage during  $t_3$ :

$$V_{N_{p1/p2},min,t_3} = (V_{out} + V_f) \cdot \frac{n_p}{n_s}$$

Min. Primary Transformer Voltage during  $t_3$ :

$$V_{N_{p1/p2},max,t_3} = -(V_{out} + V_f) \cdot \frac{n_p}{n_s}$$

### 14.3. Secondary Side Transformer Windings $N_{s1}$ and $N_{s2}$

#### 14.3.1. CCM & DCM.

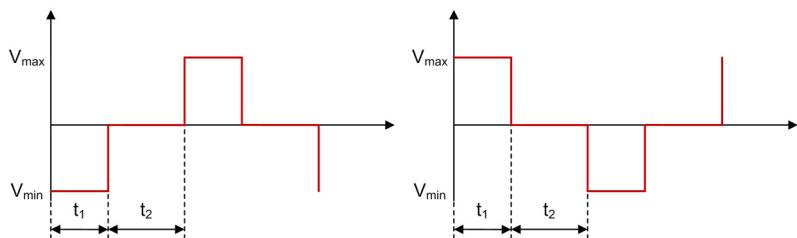


Figure 14.3.1. Push-Pull - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Voltage Waveforms in CCM

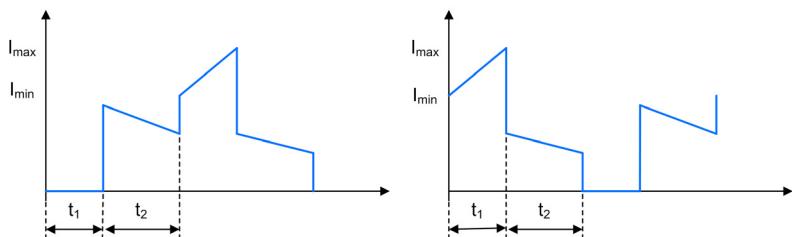


Figure 14.3.2. Push-Pull - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Current Waveforms in CCM

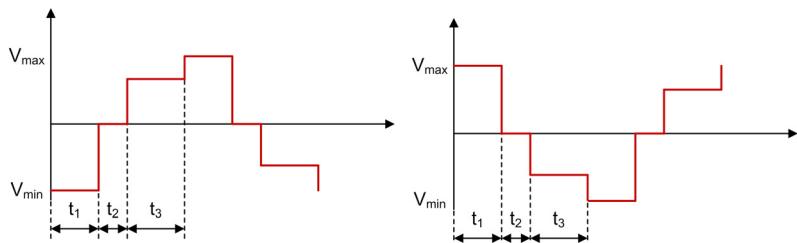


Figure 14.3.3. Push-Pull - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Voltage Waveforms in DCM

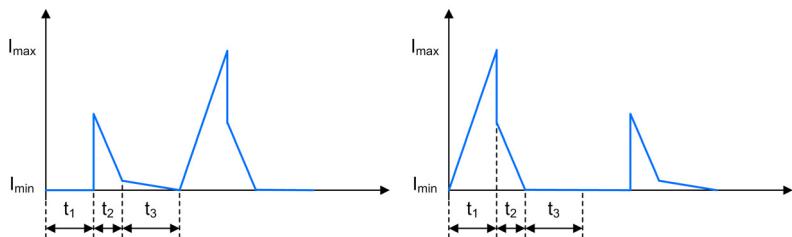


Figure 14.3.4. Push-Pull - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Current Waveforms in DCM

Average Secondary Transformer Current:	$I_{N_{s1/s2},avg} = \frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 \cdot f_{switch}$
Min. Secondary Transformer Current ( $t_1$ of FET):	$I_{N_{s1/s2},min} = I_{sec,min}$
Max. Secondary Transformer Current ( $t_1$ of FET):	$I_{N_{s1/s2},max} = I_{sec,max}$
Min. Secondary Transformer Current ( $t_2$ of other FET):	$I_{N_{s1/s2},min,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}} - \frac{I_{ripple}}{2}$
Max. Secondary Transformer Current ( $t_2$ of other FET):	$I_{N_{s1/s2},max,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}}$
Min. Secondary Transformer Current ( $t_2$ of FET, CCM):	$I_{N_{s1/s2},min,t_2} = I_{sec,min} - I_{N_{s1/s2},min,t_2,other}$
Min. Secondary Transformer Current ( $t_2$ of FET, DCM):	$I_{N_{s1/s2},min,t_2} = 0A$
Max. Secondary Transformer Current ( $t_2$ of FET):	$I_{N_{s1/s2},max,t_2} = I_{sec,max} - I_{N_{s1/s2},max,t_2,other}$
Min. Secondary Transformer Current during $t_3$ :	$I_{N_{s1/s2},min,t_3} = 0A$
Max. Secondary Transformer Current during $t_3$ :	$I_{N_{s1/s2},max,t_3} = I_{N_{s1/s2},max,t_2,other} - I_{N_{s1/s2},max,t_2}$
Min. Secondary Transformer Voltage:	$V_{N_{s1/s2},min} = -V_{in} \cdot \frac{n_s}{n_p}$
Max. Secondary Transformer Voltage:	$V_{N_{s1/s2},max} = V_{in} \cdot \frac{n_s}{n_p}$
Min. Secondary Transformer Voltage during $t_3$ :	$V_{N_{s1/s2},min,t_3} = -V_{out} - V_f$
Max. Secondary Transformer Voltage during $t_3$ :	$V_{N_{s1/s2},max,t_3} = V_{out} + V_f$

### 14.4. Inductor $L_1$

#### 14.4.1. CCM & DCM.

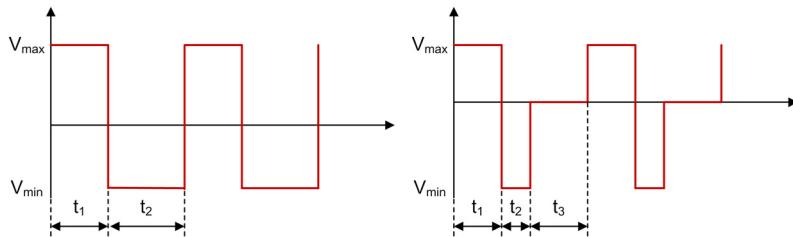


Figure 14.4.1. Push-Pull - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

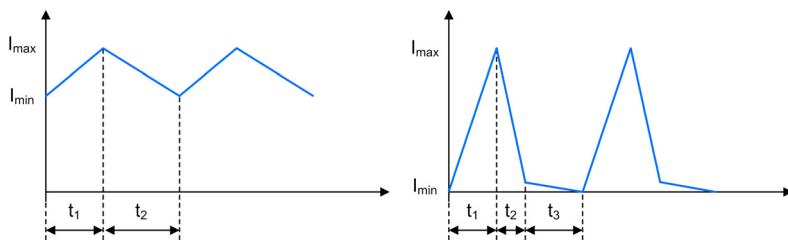


Figure 14.4.2. Push-Pull - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:  $I_{L_1,avg} = \frac{I_{sec,max} + I_{sec,min}}{2}$

Min. Inductor Current:  $I_{L_1,min} = I_{sec,min}$

Max. Inductor Current:  $I_{L_1,max} = I_{sec,max}$

Min. Inductor Current during  $t_3$ :  $I_{L_1,min,t_3} = I_{N_{s1/s2},min,t_3}$

Max. Inductor Current during  $t_3$ :  $I_{L_1,max,t_3} = I_{N_{s1/s2},max,t_3}$

Min. Inductor Voltage:  $V_{L_1,min} = -V_{out} - V_f$

Max. Inductor Voltage:  $V_{L_1,max} = V_{in} \cdot \frac{n_s}{n_p} - V_{out} - V_f$

Inductor Voltage during  $t_3$ :  $V_{L_1,t_3} = 0V$

## 14.5. FET $Q_1$ & $Q_2$

### 14.5.1. CCM.

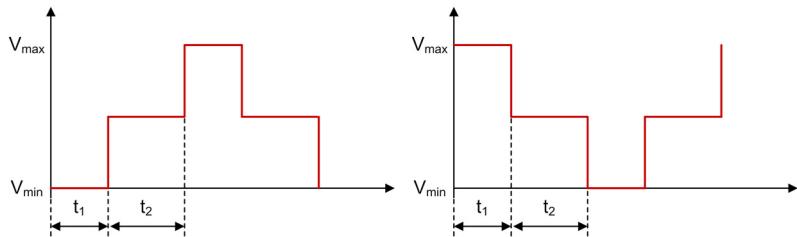


Figure 14.5.1. Push-Pull - FETs  $Q_1$  and  $Q_2$  Voltage Waveforms in CCM

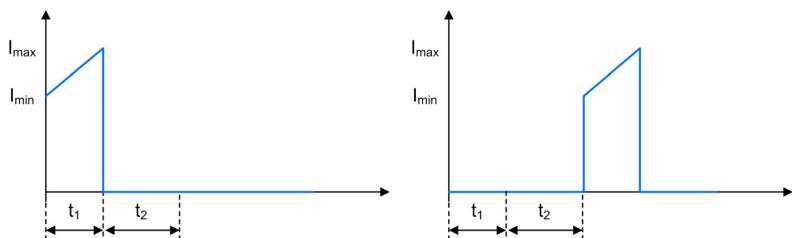


Figure 14.5.2. Push-Pull - FETs  $Q_1$  &  $Q_2$  Current Waveforms in CCM

Average FET Current:

$$I_{Q_{1/2},avg} = I_{N_{p1/p2},avg}$$

Min. FET Current:

$$I_{Q_{1/2},min} = I_{pri,min}$$

Max. FET Current:

$$I_{Q_{1/2},max} = I_{pri,max}$$

Min. FET Voltage during  $t_1$ :

$$V_{Q_{1/2},min,t_1} = 0V$$

Max. FET Voltage during  $t_1$  ( $t_1$  of other FET):

$$V_{Q_{1/2},max,t_1} = 2 \cdot V_{in}$$

FET Voltage during  $t_2$ :

$$V_{Q_{1/2},t_2} = V_{in}$$

**14.5.2. DCM.**

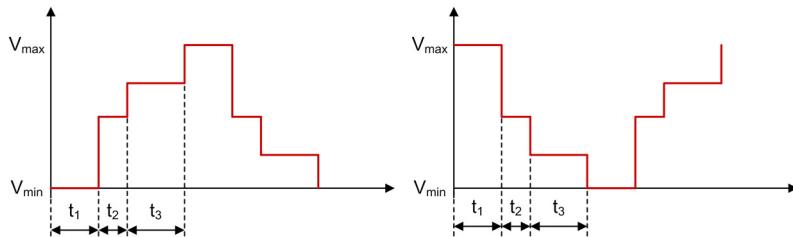


Figure 14.5.3. Push-Pull - FETs  $Q_1$  and  $Q_2$  Voltage Waveforms in DCM

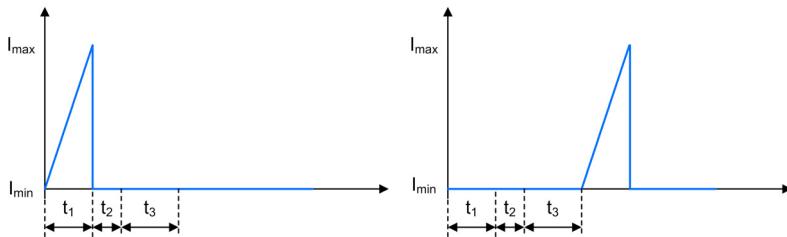


Figure 14.5.4. Push-Pull - FETs  $Q_1$  and  $Q_2$  Current Waveforms in DCM

Average FET Current:

$$I_{Q_{1/2},avg} = I_{N_{p1/p2},avg}$$

Min. FET Current:

$$I_{Q_{1/2},min} = I_{pri,min}$$

Max. FET Current:

$$I_{Q_{1/2},max} = I_{pri,max}$$

Min. FET Voltage during  $t_1$ :

$$V_{Q_{1/2},min,t_1} = 0V$$

Max. FET Voltage during  $t_1$  ( $t_1$  of other FET):

$$V_{Q_{1/2},max,t_1} = 2 \cdot V_{in}$$

FET Voltage during  $t_2$ :

$$V_{Q_{1/2},t_2} = V_{in}$$

Min. FET Voltage during  $t_3$  ( $t_3$  of other FET):

$$V_{Q_{1/2},min,t_3} = V_{in} - (V_{out} + V_f) \cdot \frac{n_p}{n_s}$$

Max. FET Voltage during  $t_3$ :

$$V_{Q_{1/2},max,t_3} = V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}$$

## 14.6. Rectifier Diode $D_1$ & $D_2$

### 14.6.1. CCM & DCM.

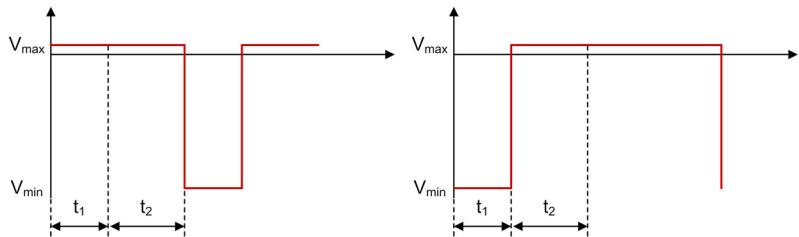


Figure 14.6.1. Push-Pull - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in CCM

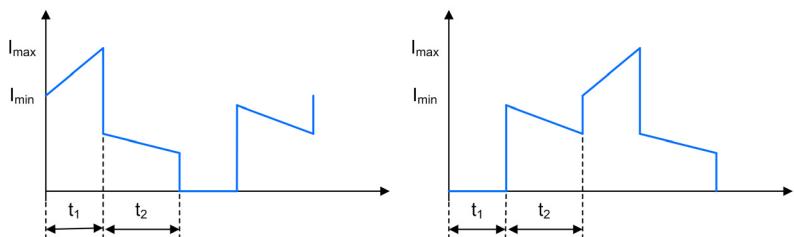


Figure 14.6.2. Push-Pull - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in CCM

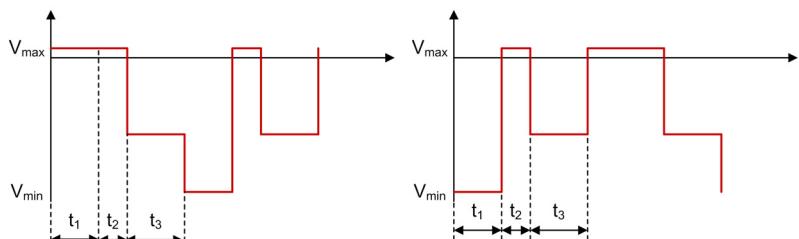


Figure 14.6.3. Push-Pull - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in DCM

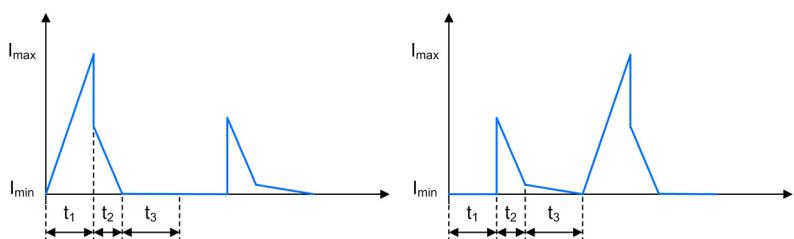


Figure 14.6.4. Push-Pull - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in DCM

Average Rectifier Diode Current:

$$I_{D_{1/2},avg} = I_{N_{s1/s2},avg}$$

Min. Rectifier Diode Current ( $t_1$  of FET):

$$I_{D_{1/2},min,t_1} = I_{sec,min}$$

Max. Rectifier Diode Current ( $t_1$  of FET):

$$I_{D_{1/2},max,t_1} = I_{sec,max}$$

Min. Rectifier Diode Current ( $t_2$  of other FET):

$$I_{D_{1/2},min,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}} - \frac{I_{ripple}}{2}$$

Max. Rectifier Diode Current ( $t_2$  of other FET):

$$I_{D_{1/2},max,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}}$$

Min. Rectifier Diode Current ( $t_2$  of FET):

$$I_{D_{1/2},min,t_2} = I_{sec,min} - I_{N_s,min,t_2,other}$$

Max. Rectifier Diode Current ( $t_2$  of FET):

$$I_{D_{1/2},max,t_2} = I_{sec,max} - I_{N_s,max,t_2,other}$$

Min. Rectifier Diode Current ( $t_3$  of other FET):

$$I_{D_{1/2},min,t_3,other} = I_{N_s,min,t_3}$$

Max. Rectifier Diode Current ( $t_3$  of other FET):

$$I_{D_{1/2},max,t_3,other} = I_{N_s,max,t_3}$$

Rectifier Diode Current ( $t_3$  of FET):

$$I_{D_{1/2},t_3} = 0A$$

Min. Rectifier Diode Voltage:

$$V_{D_{1/2},min} = -2 \cdot V_{in} \cdot \frac{n_s}{n_p} + V_f$$

Max. Rectifier Diode Voltage:

$$V_{D_{1/2},max} = V_f$$

Rectifier Diode Voltage during  $t_3$ :

$$V_{D_{1/2},t_3} = -V_{out}$$

## 14.7. Input Capacitor $C_i$

### 14.7.1. CCM & DCM.

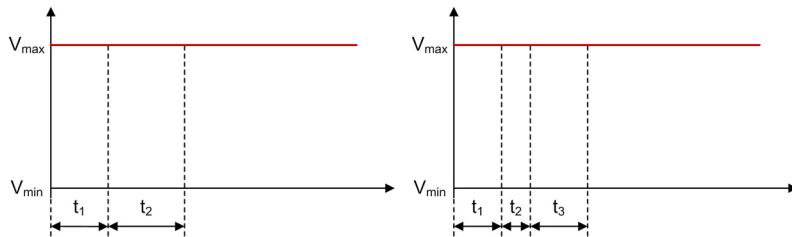


Figure 14.7.1. Push-Pull - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

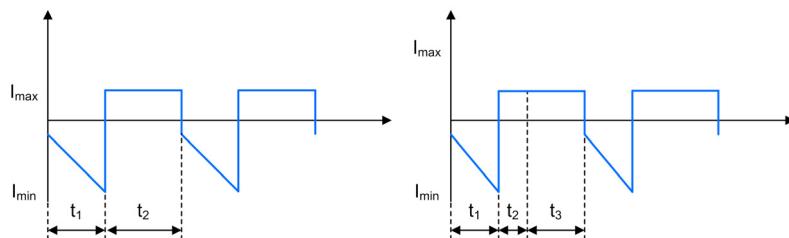


Figure 14.7.2. Push-Pull - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

Min. Input Capacitor Current during  $t_1$ :  $I_{C_i,min,t_1} = I_{N_p,avg} - I_{N_p,max}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_i,max,t_1} = I_{N_p,avg} - I_{N_p,min}$

Input Capacitor Current during  $t_2$  and  $t_3$ :  $I_{C_i,t_{2/3}} = I_{N_p,avg}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

## 14.8. Output Capacitor $C_o$

### 14.8.1. CCM & DCM.

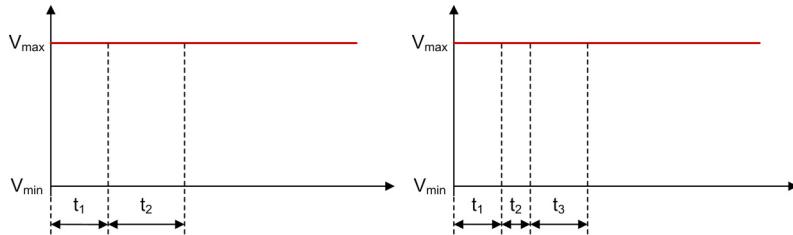


Figure 14.8.1. Push-Pull - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

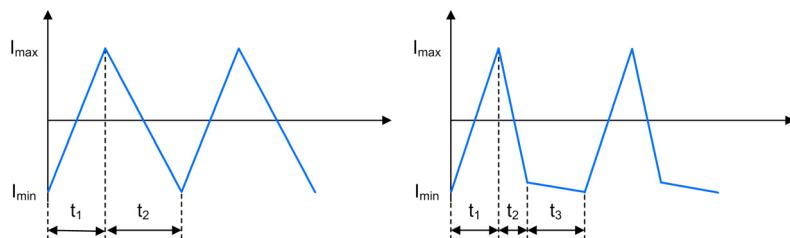


Figure 14.8.2. Push-Pull - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Min. Output Capacitor Current:  $I_{C_o,min} = I_{sec,min} - I_{out}$

Max. Output Capacitor Current:  $I_{C_o,max} = I_{sec,max} - I_{out}$

Min. Output Capacitor Current during  $t_3$ :  $I_{C_o,min,t_3} = I_{sec,min} - I_{out}$

Max. Output Capacitor Current during  $t_3$ :  $I_{C_o,max,t_3} = I_{N_s,max,t_3} - I_{out}$

Average Output Capacitor Current:  $I_{C_o,avg} = 0A$

Output Capacitor Voltage:  $V_{C_o} = V_{out}$

# Weinberg Converter

A Weinberg regulator is a Flyback current fed Push-Pull regulator and converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output both when the FETs are conducting and not conducting.

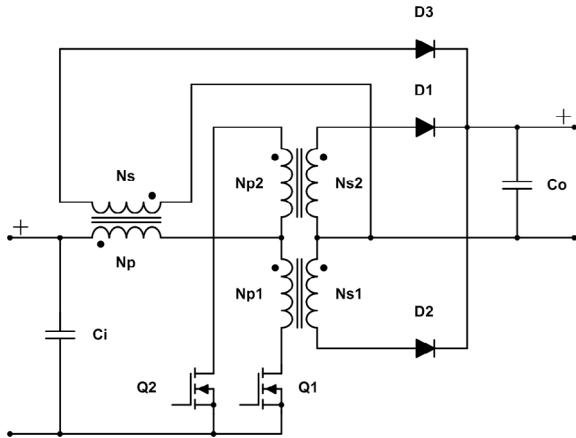


Figure 15.0.1. Schematic of a Weinberg converter

## 15.1. General

$$\text{Secondary Side Inductance (Push-Pull): } L_{s,pushpull} = \frac{L_{p,pushpull}}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Secondary Side Inductance (Flyback): } L_{s,flyback} = \frac{L_{p,flyback}}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{(V_{in} - (V_{out} + V_f) \cdot \frac{n_p}{n_s}) \cdot t_1}{L_{p,flyback}}$$

$$\text{Magnetization Current: } I_{mag} = \frac{(V_{out} + V_f) \cdot \frac{n_p}{n_s} \cdot t_1}{L_{p,pushpull}}$$

### 15.1.1. Continuous Conduction Mode.

$$\text{FET on, increasing current: } t_1 = \frac{1}{2 \cdot f_{switch}} \cdot \frac{V_{out} + V_f}{V_{in} \cdot \frac{n_s}{n_p}}$$

$$\text{FET off, decreasing current: } t_2 = \frac{1}{2 \cdot f_{switch}} - t_1$$

$$\text{Average Input Pulse Current: } I_{in,pulse,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}} \cdot \frac{1}{2 \cdot D}$$

$$\text{Min. Primary Current: } I_{pri,min} = I_{in,pulse,avg} - \frac{I_{ripple}}{2}$$

$$\text{Max. Primary Current: } I_{pri,max} = I_{in,pulse,avg} + \frac{I_{ripple}}{2}$$

## 15.2. Primary Side Flyback Inductor $N_p$

### 15.2.1. CCM.

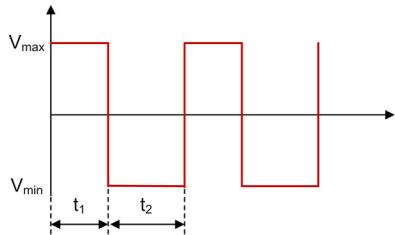


Figure 15.2.1. Weinberg - Primary Side Flyback Inductor  $N_p$  Voltage Waveform in CCM

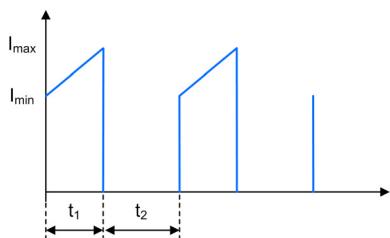


Figure 15.2.2. Weinberg - Primary Side Flyback Inductor  $N_p$  Current Waveform in CCM

Average Primary Flyback Inductor Current:  $I_{N_p,avg} = \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \cdot 2 \cdot f_{switch}$

Min. Primary Flyback Inductor Current:  $I_{N_p,min} = I_{pri,min}$

Max. Primary Flyback Inductor Current:  $I_{N_p,max} = I_{pri,max}$

Min. Primary Flyback Inductor Voltage:  $V_{N_p,min} = -(V_{out} + V_f) \cdot \frac{n_p}{n_s}$

Max. Primary Flyback Inductor Voltage:  $V_{N_p,i,max} = V_{in} - (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

### 15.3. Secondary Side Flyback Inductor $N_s$

#### 15.3.1. CCM.

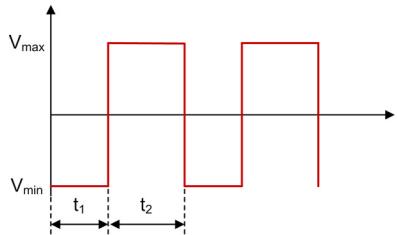


Figure 15.3.1. Weinberg - Secondary Side Flyback Inductor  $N_s$  Voltage Waveform in CCM

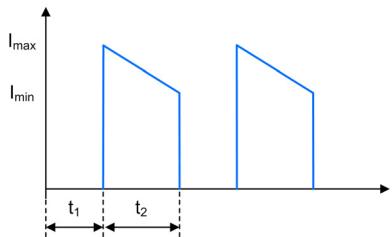


Figure 15.3.2. Weinberg - Secondary Side Flyback Inductor  $N_s$  Current Waveform in CCM

Min. Secondary Flyback Transformer Current:

$$I_{N_s,\text{min}} = I_{\text{pri},\text{min}} \cdot \frac{n_p}{n_s}$$

Max. Secondary Flyback Transformer Current:

$$I_{N_s,\text{max}} = I_{\text{pri},\text{max}} \cdot \frac{n_p}{n_s}$$

Average Secondary Flyback Transformer Current:

$$I_{N_s,\text{avg}} = \frac{I_{N_s,\text{min}} + I_{N_s,\text{max}}}{2} \cdot t_2 \cdot 2 \cdot f_{\text{switch}}$$

Min. Secondary Flyback Transformer Voltage:

$$V_{N_s,\text{min}} = -V_{N_p,\text{max}} \cdot \frac{n_s}{n_p}$$

Max. Secondary Flyback Transformer Voltage:

$$V_{N_s,\text{max}} = -V_{N_p,\text{min}} \cdot \frac{n_s}{n_p}$$

## 15.4. Primary Side Push-Pull Transformer Windings $N_{p1}$ & $N_{p2}$

### 15.4.1. CCM.

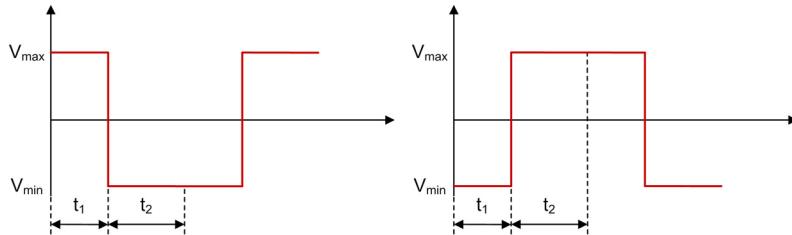


Figure 15.4.1. Weinberg - Primary Side Push-Pull Transformer Windings  $N_{p1}$  and  $N_{p2}$  Voltage Waveforms in CCM

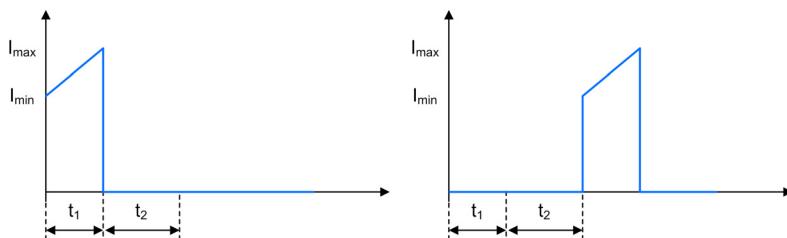


Figure 15.4.2. Weinberg - Primary Side Push-Pull Transformer Windings  $N_{p1}$  and  $N_{p2}$  Current Waveforms in CCM

$$\text{Average Primary Push-Pull Transformer Current: } I_{N_{p1/p2},avg} = \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$$

$$\text{Min. Primary Push-Pull Transformer Current: } I_{N_{p1/p2},min} = I_{pri,min}$$

$$\text{Max. Primary Push-Pull Transformer Current: } I_{N_{p1/p2},max} = I_{pri,max}$$

$$\text{Min. Primary Push-Pull Transformer Voltage: } V_{N_{p1/p2},min} = -(V_{out} + V_f) \cdot \frac{n_p}{n_s}$$

$$\text{Max. Primary Push-Pull Transformer Voltage: } V_{N_{p1/p2},max} = (V_{out} + V_f) \cdot \frac{n_p}{n_s}$$

## 15.5. Secondary Side Push-Pull Transformer Windings $N_{s1}$ & $N_{s2}$

### 15.5.1. CCM.

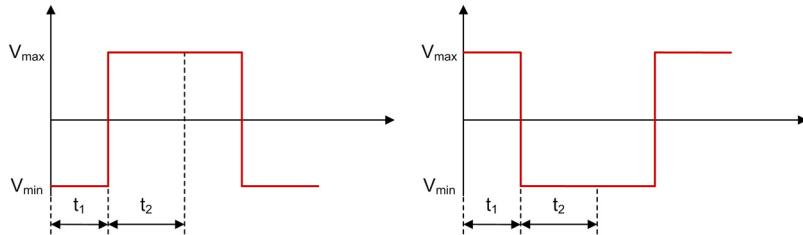


Figure 15.5.1. Weinberg - Secondary Side Push-Pull Transformer Windings  $N_{s1}$  and  $N_{s2}$  Voltage Waveforms in CCM

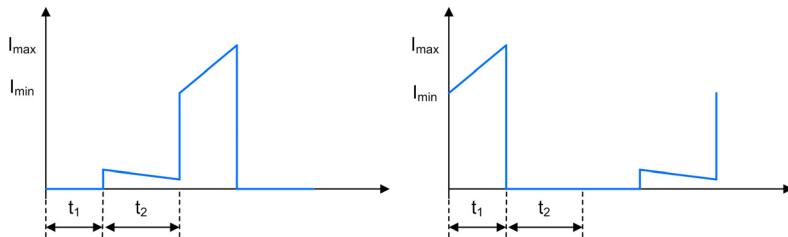


Figure 15.5.2. Weinberg - Secondary Side Push-Pull Transformer Windings  $N_{s1}$  and  $N_{s2}$  Current Waveforms in CCM

$$\text{Min. Secondary Push-Pull Transformer Current during } t_1: \quad I_{N_{s1/s2},min,t_1} = (I_{pri,min} + \frac{(1-D) \cdot I_{mag}}{2}) \cdot \frac{n_p}{n_s}$$

$$\text{Max. Secondary Push-Pull Transformer Current during } t_1: \quad I_{N_{s1/s2},max,t_1} = (I_{pri,min} - \frac{(1+D) \cdot I_{mag}}{2}) \cdot \frac{n_p}{n_s}$$

$$\text{Min. Secondary Push-Pull Transformer Current during } t_2: \quad I_{N_{s1/s2},min,t_2} = I_{N_{s1/s2},min,t_1} - I_{N_s,min}$$

$$\text{Max. Secondary Push-Pull Transformer Current during } t_2: \quad I_{N_{s1/s2},max,t_2} = I_{N_{s1/s2},max,t_1} - I_{N_s,min}$$

Average Secondary Push-Pull Transformer Current:

$$I_{N_{s1/s2},avg} = \frac{I_{N_{s1/s2},min,t_1} + I_{N_{s1/s2},max,t_1}}{2} \cdot t_1 \cdot f_{switch} + \frac{I_{N_{s1/s2},min,t_2} + I_{N_{s1/s2},max,t_2}}{2} \cdot t_2 \cdot f_{switch}$$

$$\text{Min. Secondary Push-Pull Transformer Voltage:} \quad V_{N_{s1/s2},min} = V_{N_{p1/p2},min} \cdot \frac{n_s}{n_p}$$

$$\text{Max. Secondary Push-Pull Transformer Voltage:} \quad V_{N_{s1/s2},max} = V_{N_{p1/p2},max} \cdot \frac{n_s}{n_p}$$

## 15.6. FET $Q_1$ & $Q_2$

### 15.6.1. CCM.

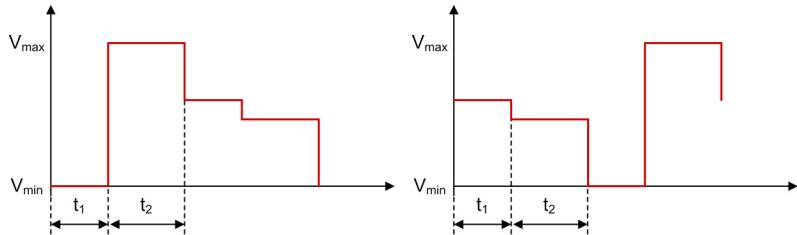


Figure 15.6.1. Weinberg - FET  $Q_1$  and  $Q_2$  Voltage Waveforms in CCM

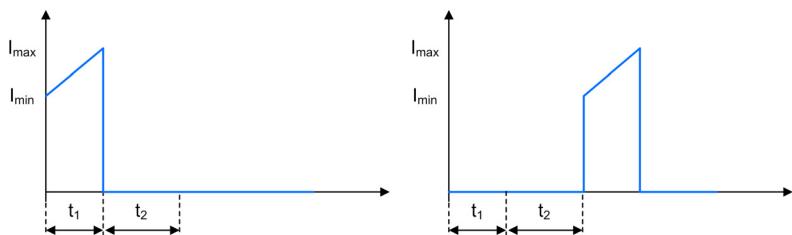


Figure 15.6.2. Weinberg - FET  $Q_1$  and  $Q_2$  Current Waveforms in CCM

Average FET Current:  $I_{Q_{1/2},avg} = I_{N_p,avg}$

Min. FET Current:  $I_{Q_{1/2},min} = I_{pri,min}$

Max. FET Current:  $I_{Q_{1/2},max} = I_{pri,max}$

Min. FET Voltage:  $V_{Q_{1/2},min} = 0V$

FET Voltage ( $t_2$  of other FET):  $V_{Q_{1/2},otheroff} = V_{in}$

FET Voltage ( $t_1$  of other FET):  $V_{Q_{1/2},otheron} = 2 \cdot \frac{n_p}{n_s} \cdot (V_{out} + V_f)$

Max. FET Voltage ( $t_2$  of FET):  $V_{Q_{1/2},max} = V_{in} + 2 \cdot \frac{n_p}{n_s} \cdot (V_{out} + V_f)$

## 15.7. Push-Pull Rectifier Diodes $D_1$ & $D_2$

### 15.7.1. CCM.

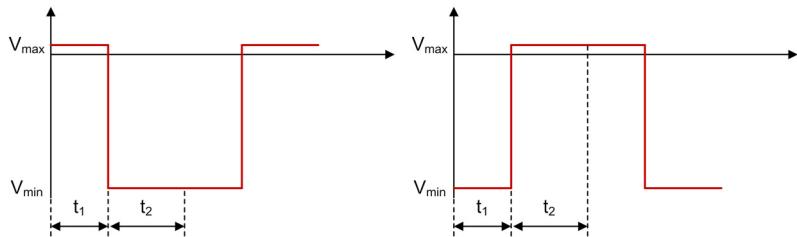


Figure 15.7.1. Weinberg - Push-Pull Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in CCM

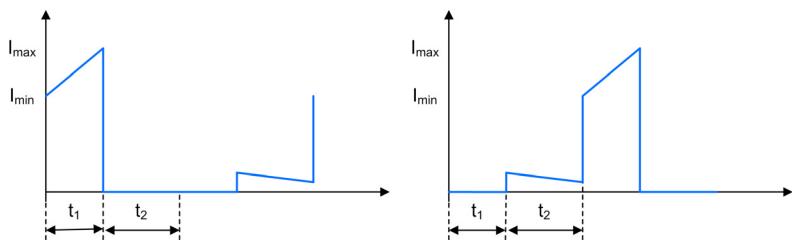


Figure 15.7.2. Weinberg - Push-Pull Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in CCM

Average Rectifier Diode Current:  $I_{D_{1/2},avg} = I_{pushpull,sec,avg}$

Min. Rectifier Diode Current during  $t_1$ :  $I_{D_{1/2},min,t_1} = I_{N_{s1/s2},min,t_1}$

Max. Rectifier Diode Current during  $t_1$ :  $I_{D_{1/2},max,t_1} = I_{N_{s1/s2},max,t_1}$

Min. Rectifier Diode Current during  $t_2$ :  $I_{D_{1/2},min,t_2} = I_{N_{s1/s2},min,t_2}$

Max. Rectifier Diode Current during  $t_2$ :  $I_{D_{1/2},max,t_2} = I_{N_{s1/s2},max,t_2}$

Min. Rectifier Diode Voltage:  $V_{D_{1/2},min} = 2 \cdot V_{N_{p1/p2},min} \cdot \frac{n_s}{n_p}$

Max. Rectifier Diode Voltage:  $V_{D_{1/2},max} = V_f$

## 15.8. Flyback Demagnetization Diode $D_3$

### 15.8.1. CCM.

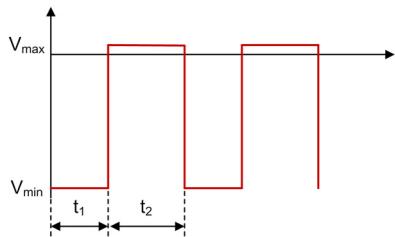


Figure 15.8.1. Weinberg - Flyback Demagnetization Diode  $D_3$  Voltage Waveform in CCM

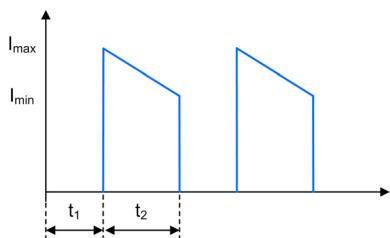


Figure 15.8.2. Weinberg - Flyback Demagnetization Diode  $D_3$  Current Waveform in CCM

Average Demagnetization Diode Current:  $I_{D_3,avg} = I_{N_s,avg}$

Demagnetization Diode Current during  $t_1$ :  $I_{D_3,t_1} = 0A$

Min. Demagnetization Diode Current during  $t_2$ :  $I_{D_3,min,t_2} = I_{N_s,min}$

Max. Demagnetization Diode Current during  $t_2$ :  $I_{D_3,max,t_2} = I_{N_s,max}$

Min. Demagnetization Diode Voltage:  $V_{D_3,min} = V_{N_s,min} - V_{out}$

Max. Demagnetization Diode Voltage:  $V_{D_3,max} = V_f$

## 15.9. Input Capacitor $C_i$

### 15.9.1. CCM.

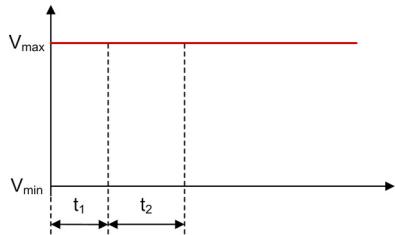


Figure 15.9.1. Weinberg - Input Capacitor  $C_i$  Voltage Waveform in CCM

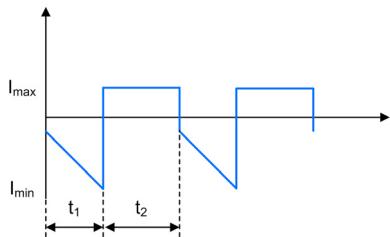


Figure 15.9.2. Weinberg - Input Capacitor  $C_i$  Current Waveform in CCM

Min. Input Capacitor Current during  $t_1$ :  $I_{C_i,min,t_1} = I_{N_p,avg} - I_{N_{p1/p2},max}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_i,max,t_1} = I_{N_p,avg} - I_{N_{p1/p2},min}$

Input Capacitor Current during  $t_2$ :  $I_{C_i,t_2} = I_{N_p,avg}$

Average Input Capacitor Current:  $I_{C_i,avg} = 0A$

Input Capacitor Voltage:  $V_{C_i} = V_{in}$

## 15.10. Output Capacitor $C_o$

### 15.10.1. CCM.

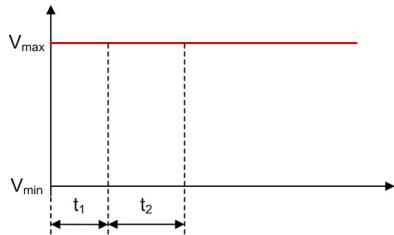


Figure 15.10.1. Weinberg - Output Capacitor  $C_o$  Voltage Waveform in CCM

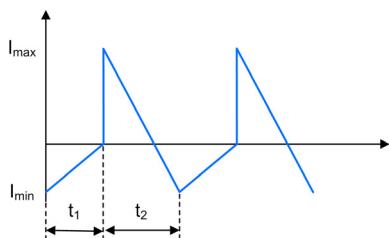


Figure 15.10.2. Weinberg - Output Capacitor  $C_o$  Current Waveform in CCM

$$\text{Min. Output Capacitor Current during } t_1: \quad I_{C_o,min,t_1} = I_{D_{1/2},min,t_1} - I_{out}$$

$$\text{Max. Output Capacitor Current during } t_1: \quad I_{C_o,max,t_1} = I_{D_{1/2},max,t_1} - I_{out}$$

$$\text{Min. Output Capacitor Current during } t_2: \quad I_{C_o,min,t_2} = I_{D_3,min,t_2} + I_{D_{1/2},min,t_2} - I_{out}$$

$$\text{Max. Output Capacitor Current during } t_2: \quad I_{C_o,max,t_2} = I_{D_3,max,t_2} + I_{D_{1/2},max,t_2} - I_{out}$$

$$\text{Average Output Capacitor Current:} \quad I_{C_o,avg} = 0A$$

$$\text{Output Capacitor Voltage:} \quad V_{C_o} = V_{out}$$



# Half-Bridge Converter

A Half-Bridge regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FETs are conducting.

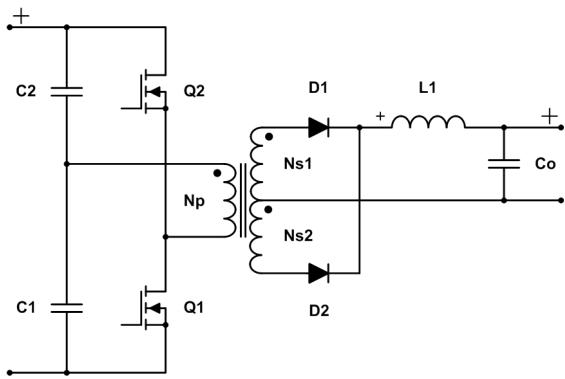


Figure 16.0.1. Schematic of a Half-Bridge converter

### 15.1. General

$$\text{Secondary Side Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot \left( \frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out} \right) \cdot t_1$$

$$\text{Magnetization Current: } I_{mag} = \frac{1}{2} \cdot \frac{V_{in} \cdot t_1}{L_p}$$

### 16.1.1. Continuous Conduction Mode.

FET on, increasing current:  $t_1 = \frac{1}{f_{switch}} \cdot \frac{V_{out} + V_f}{V_{in} \cdot \frac{n_s}{n_p}}$

FET off, decreasing current:  $t_2 = \frac{1}{2 \cdot f_{switch}} - t_1$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,min} = I_{sec,min} \cdot \frac{n_s}{n_p} - \frac{1}{2} \cdot I_{mag}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

### 16.1.2. Discontinuous Conduction Mode.

FET on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out} + V_f}{2 \cdot f_{switch} \cdot \left( \frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out} \right) \cdot \left( \frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p} \right)}}$

FET off, decreasing current:  $t_2 = t_1 \cdot \frac{\frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p}}{(V_{out} + V_f)} - t_1$

FET off, demagnetization:  $t_3 = \frac{1}{2 \cdot f_{switch}} - t_1 - t_2$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{ripple}$

Min. Primary Current:  $I_{pri,max} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

## 16.2. Primary Side Transformer Winding $N_p$

### 16.2.1. CCM & DCM.

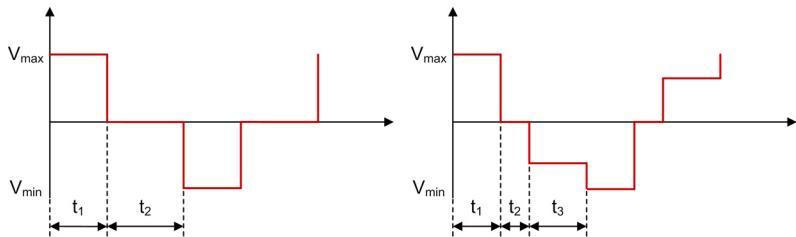


Figure 16.2.1. Half-Bridge - Primary Side Transformer Winding  $N_p$  Voltage Waveforms in CCM and DCM

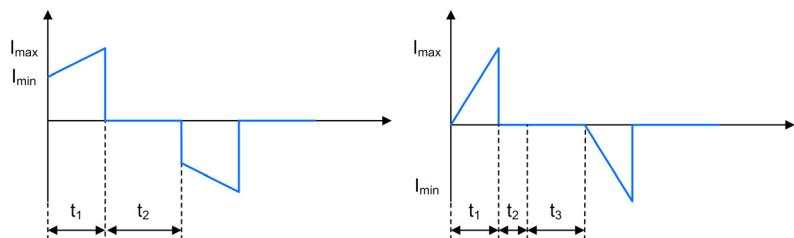


Figure 16.2.2. Half-Bridge - Primary Side Transformer Winding  $N_p$  Current Waveforms in CCM and DCM

Average Primary Transformer Current:  $I_{N_p,\text{avg}} = 0A$

Min. Primary Transformer Current:  $I_{N_p,\text{min}} = I_{\text{pri,min}}$

Max. Primary Transformer Current:  $I_{N_p,\text{max}} = I_{\text{pri,max}}$

Min. Primary Transformer Voltage:  $V_{N_p,\text{min}} = -\frac{1}{2} \cdot V_{\text{in}}$

Max. Primary Transformer Voltage:  $V_{N_p,\text{max}} = \frac{1}{2} \cdot V_{\text{in}}$

Min. Primary Transformer Voltage during  $t_3$ :  $V_{N_p,t_3} = (V_{\text{out}} + V_f) \cdot \frac{n_p}{n_s}$

### 16.3. Secondary Side Transformer Winding $N_{s_1}$ & $N_{s_2}$

#### 16.3.1. CCM & DCM.

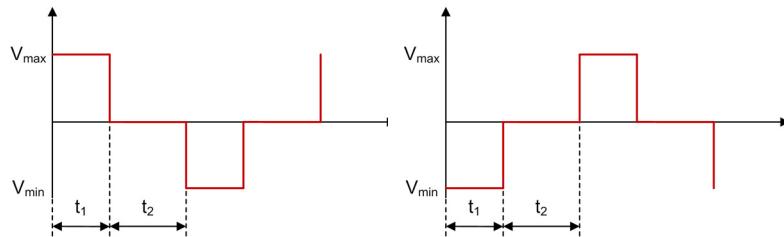


Figure 16.3.1. Half-Bridge - Secondary Side Transformer Windings  $N_{s_1}$  and  $N_{s_2}$  Voltage Waveforms in CCM

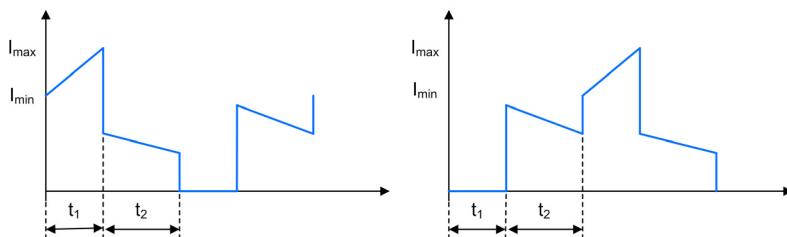


Figure 16.3.2. Half-Bridge - Secondary Side Transformer Windings  $N_{s_1}$  and  $N_{s_2}$  Current Waveforms in CCM

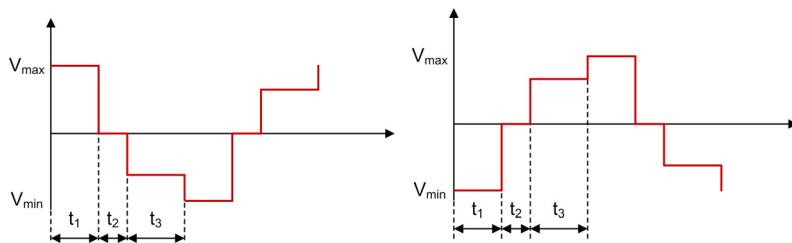


Figure 16.3.3. Half-Bridge - Secondary Side Transformer Windings  $N_{s_1}$  and  $N_{s_2}$  Voltage Waveforms in DCM

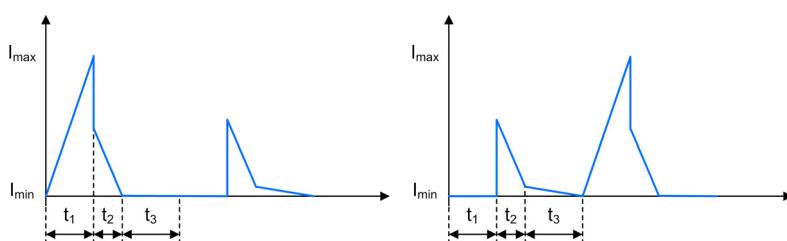


Figure 16.3.4. Half-Bridge - Secondary Side Transformer Windings  $N_{s_1}$  and  $N_{s_2}$  Current Waveforms in DCM

Min. Secondary Current ( $t_1$ of FET):	$I_{N_{s1/s2},min,t_1} = I_{sec,min}$
Max. Secondary Current ( $t_1$ of FET):	$I_{N_{s1/s2},max,t_1} = I_{sec,max}$
Min. Secondary Current ( $t_2$ of other FET):	$I_{N_{s1/s2},min,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}} - \frac{I_{ripple}}{2}$
Max. Secondary Current ( $t_2$ of other FET):	$I_{N_{s1/s2},max,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}}$
Min. Secondary Current ( $t_2$ of FET, CCM):	$I_{N_{s1/s2},min,t_2} = I_{sec,min} - I_{N_{s1/s2},min,t_2,other}$
Min. Secondary Current ( $t_2$ of FET, DCM):	$I_{N_{s1/s2},min,t_2} = 0A$
Max. Secondary Current ( $t_2$ of FET):	$I_{N_{s1/s2},max,t_2} = I_{sec,max} - I_{N_{s1/s2},max,t_2,other}$
Min. Secondary Current ( $t_3$ of other FET):	$I_{N_{s1/s2},min,t_3,other} = 0A$
Max. Secondary Current ( $t_3$ of other FET):	$I_{N_{s1/s2},max,t_3,other} = I_{N_{s1/s2},max,t_2,other} - I_{N_{s1/s2},max,t_2}$
Secondary Current ( $t_3$ of FET):	$I_{N_{s1/s2},t_3} = 0A$
Average Secondary Current:	
$I_{N_{s1/s2},avg} = f_{switch} \cdot \left( \frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 + \frac{I_{N_{s1/s2},max,t_2} + I_{N_{s1/s2},min,t_2,other}}{2} \cdot t_2 + \frac{I_{N_{s1/s2},min,t_2} + I_{N_{s1/s2},max,t_2,other}}{2} \cdot t_3 \right)$	
Min. Secondary Voltage:	$V_{N_{s1/s2},min} = -\frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p}$
Max. Secondary Voltage:	$V_{N_{s1/s2},max} = \frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p}$
Secondary Voltage during $t_3$ :	$V_{N_{s1/s2},max,t_3} = V_{out} + V_f$

## 16.4. Inductor $L_1$

### 16.4.1. CCM & DCM.

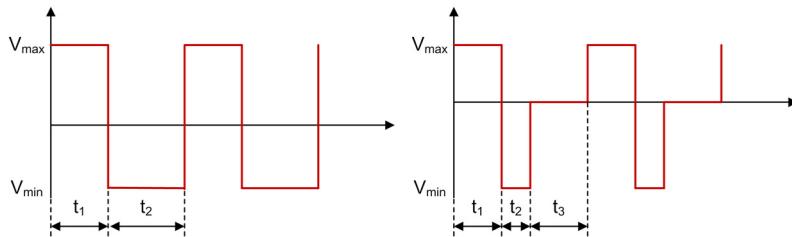


Figure 16.4.1. Half-Bridge - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

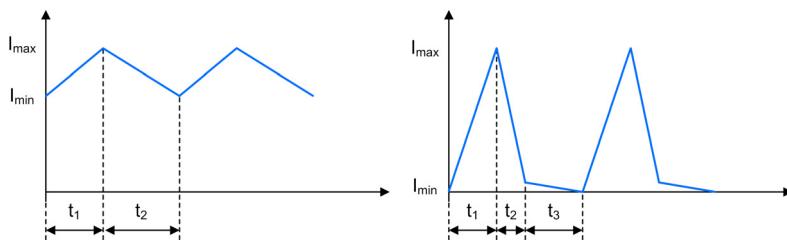


Figure 16.4.2. Half-Bridge - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:  $I_{L_1,avg} = \frac{I_{sec,max} + I_{sec,min}}{2}$

Min. Inductor Current:  $I_{L_1,min} = I_{sec,min}$

Max. Inductor Current:  $I_{L_1,max} = I_{sec,max}$

Min. Inductor Current during  $t_3$ :  $I_{L_1,min,t_3} = I_{N_{s1/s2},min,t_3}$

Max. Inductor Current during  $t_3$ :  $I_{L_1,max,t_3} = I_{N_{s1/s2},max,t_3}$

Min. Inductor Voltage:  $V_{L_1,min} = -V_{out} - V_f$

Max. Inductor Voltage:  $V_{L_1,max} = \frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}$

Inductor Voltage during  $t_3$ :  $V_{L_1,t_3} = 0V$

## 16.5. FET $Q_1$ & $Q_2$

### 16.5.1. CCM & DCM.

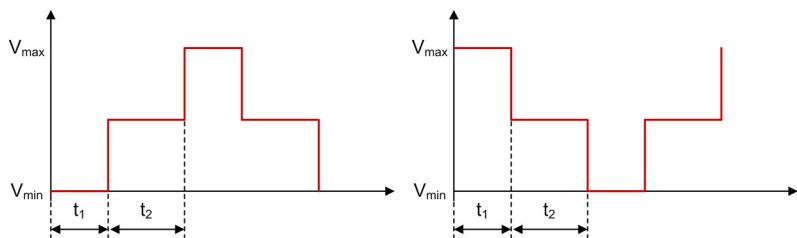


Figure 16.5.1. Half-Bridge - FETs  $Q_1$  and  $Q_2$  Voltage Waveforms in CCM

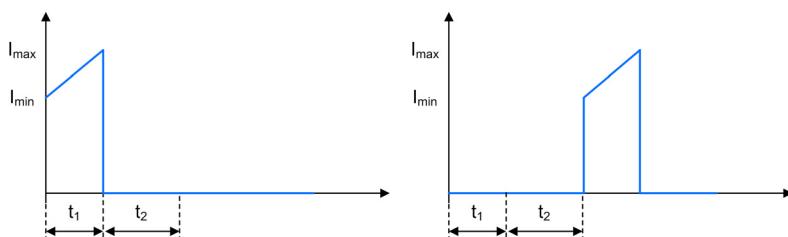


Figure 16.5.2. Half-Bridge - FETs  $Q_1$  and  $Q_2$  Current Waveforms in CCM

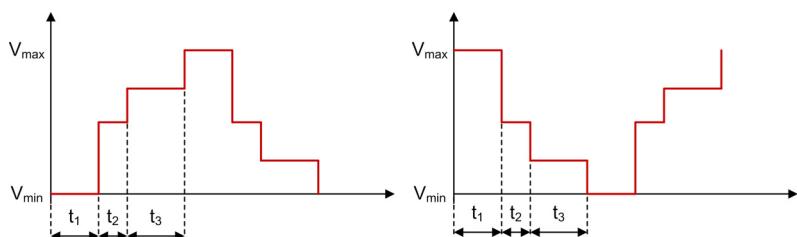


Figure 16.5.3. Half-Bridge - FETs  $Q_1$  and  $Q_2$  Voltage Waveforms in DCM

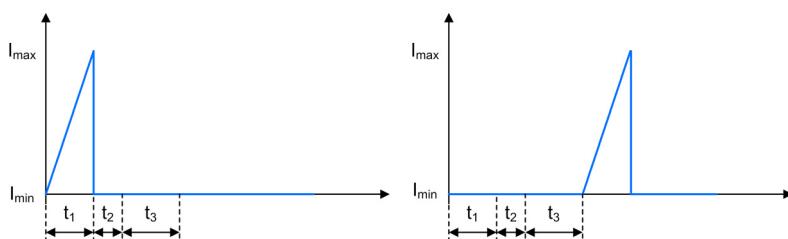


Figure 16.5.4. Half-Bridge - FETs  $Q_1$  and  $Q_2$  Current Waveforms in DCM

Average FET Current:  $I_{Q_{1/2},avg} = \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$

Min. FET Current:  $I_{Q_{1/2},min} = I_{pri,min}$

Max. FET Current:  $I_{Q_{1/2},max} = I_{pri,max}$

Min. FET Voltage during  $t_1$ :  $V_{Q_{1/2},min,t_1} = 0V$

Max. FET Voltage during  $t_1$ :  $V_{Q_{1/2},max,t_1} = V_{in}$

FET Voltage during  $t_2$ :  $V_{Q_{1/2},t_2} = \frac{1}{2} \cdot V_{in}$

Min. FET Voltage during  $t_3$ :  $V_{Q_{1/2},min,t_3} = \frac{V_{in}}{2} - (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

Max. FET Voltage during  $t_3$ :  $V_{Q_{1/2},max,t_3} = \frac{V_{in}}{2} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

## 16.6. Rectifier Diode $D_1$ & $D_2$

### 16.6.1. CCM & DCM.

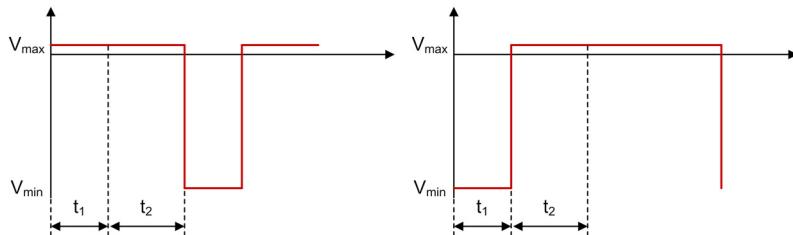


Figure 16.6.1. Half-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in CCM

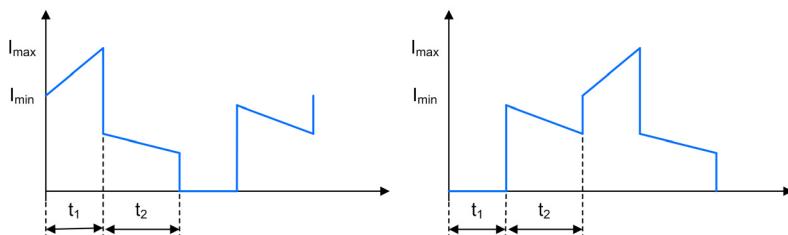


Figure 16.6.2. Half-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in CCM

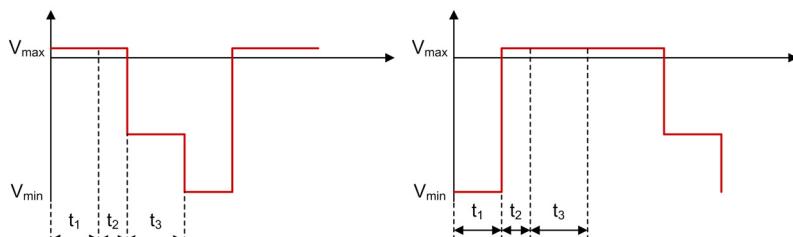


Figure 16.6.3. Half-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in DCM

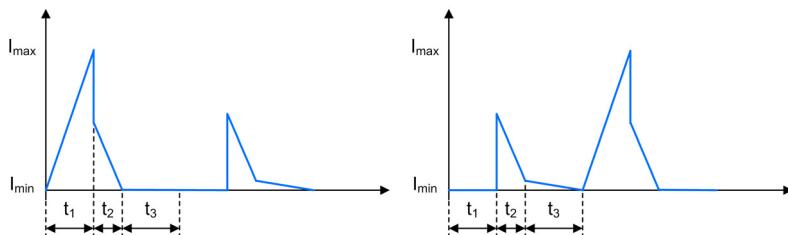


Figure 16.6.4. Half-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in DCM

Average Rectifier Diode Current:	$I_{D_{1/2},avg} = I_{N_{s1/s2},avg}$
Min. Rectifier Diode Current ( $t_1$ of FET):	$I_{D_{1/2},min} = I_{N_{s1/s2},min}$
Max. Rectifier Diode Current ( $t_1$ of FET):	$I_{D_{1/2},max} = I_{N_{s1/s2},max}$
Min. Rectifier Diode Current ( $t_2$ of other FET):	$I_{D_{1/2},min,t_2,other} = I_{N_{s1/s2},min,t_2,other}$
Max. Rectifier Diode Current ( $t_2$ of other FET):	$I_{D_{1/2},max,t_2,other} = I_{N_{s1/s2},max,t_2,other}$
Min. Rectifier Diode Current ( $t_2$ of FET):	$I_{D_{1/2},min,t_2} = I_{N_{s1/s2},min,t_2}$
Max. Rectifier Diode Current ( $t_2$ of FET):	$I_{D_{1/2},max,t_2} = I_{N_{s1/s2},max,t_2}$
Min. Rectifier Diode Current ( $t_3$ of other FET):	$I_{D_{1/2},min,t_3,other} = I_{N_{s1/s2},min,t_3}$
Max. Rectifier Diode Current ( $t_3$ of other FET):	$I_{D_{1/2},max,t_3,other} = I_{N_{s1/s2},max,t_3}$
Rectifier Diode Current ( $t_3$ of FET):	$I_{D_{1/2},t_3} = 0A$
Min. Rectifier Diode Voltage:	$V_{D_{1/2},min} = -V_{in} \cdot \frac{n_s}{n_p} + V_f$
Max. Rectifier Diode Voltage:	$V_{D_{1/2},max} = V_f$
Rectifier Diode Voltage during $t_3$ :	$V_{D_{1/2},t_3} = -V_{in} \cdot \frac{n_p}{n_s}$

## 16.7. Input Capacitor $C_1$ & $C_2$

### 16.7.1. CCM & DCM.

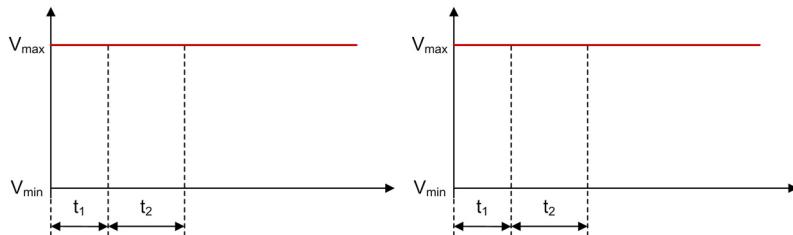


Figure 16.7.1. Half-Bridge - Input Capacitor  $C_1$  and  $C_2$  Voltage Waveforms in CCM

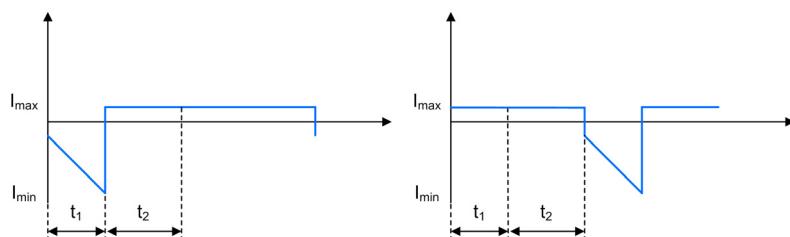


Figure 16.7.2. Half-Bridge - Input Capacitor  $C_1$  and  $C_2$  Current Waveforms in CCM

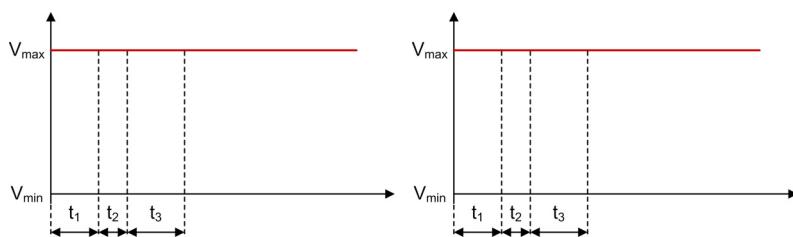


Figure 16.7.3. Half-Bridge - Input Capacitor  $C_1$  and  $C_2$  Voltage Waveforms in DCM

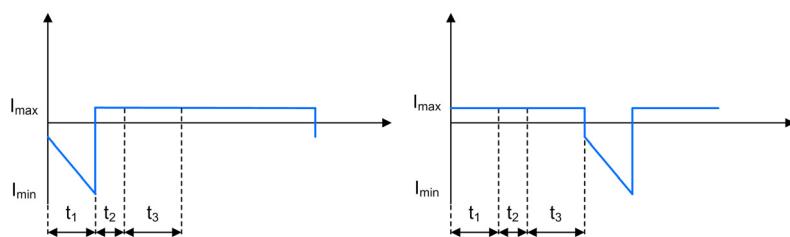


Figure 16.7.4. Half-Bridge - Input Capacitor  $C_1$  and  $C_2$  Current Waveforms in DCM

Min. Input Capacitor Current during  $t_1$ :  $I_{C_{1/2},min,t_1} = I_{Q_{1/2},avg} - I_{N_p,max}$

Max. Input Capacitor Current during  $t_1$ :  $I_{C_{1/2},max,t_1} = I_{Q_{1/2},avg} - I_{N_p,min}$

Input Capacitor Current during  $t_2$  and  $t_3$ :  $I_{C_{1/2},t_{2/3}} = I_{Q_{1/2},avg}$

Average Input Capacitor Current:  $I_{C_{1/2},avg} = 0A$

Input Capacitor Voltage:  $V_{C_{1/2}} = V_{in}$

## 16.8. Output Capacitor $C_o$

### 16.8.1. CCM & DCM.

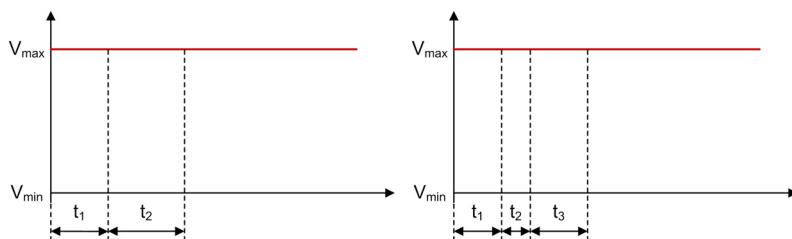


Figure 16.8.1. Half-Bridge - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

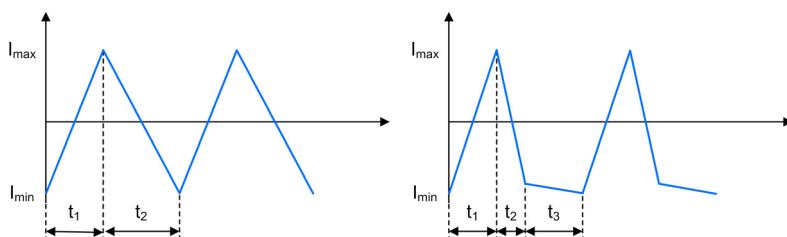


Figure 16.8.2. Half-Bridge - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Min. Output Capacitor Current:  $I_{C_o,min} = I_{sec,min} - I_{out}$

Max. Output Capacitor Current:  $I_{C_o,max} = I_{sec,max} - I_{out}$

Min. Output Capacitor Current during  $t_3$ :  $I_{C_o,min,t_3} = I_{sec,min} - I_{out}$

Max. Output Capacitor Current during  $t_3$ :  $I_{C_o,max,t_3} = I_{N_{s1/s2},max,t_3} - I_{out}$

Average Output Capacitor Current:  $I_{C_o,avg} = 0A$

Output Capacitor Voltage:  $V_{C_o} = V_{out}$



# Full-Bridge Converter

A Full-Bridge regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the FETs are conducting.

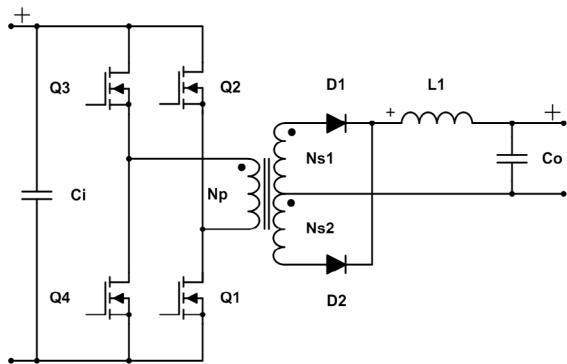


Figure 17.0.1. Schematic of a Full-Bridge converter

### 17.1. General

$$\text{Secondary Side Inductance: } L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

$$\text{Inductor Current Ripple: } I_{ripple} = \frac{1}{L_1} \cdot \left( V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out} \right) \cdot t_1$$

$$\text{Magnetization Current: } I_{mag} = \frac{V_{in} \cdot t_1}{L_p}$$

### 17.1.1. Continuous Conduction Mode.

FETs on, increasing current:  $t_1 = \frac{1}{2 \cdot f_{switch}} \cdot \frac{V_{out} + V_f}{V_{in} \cdot \frac{n_s}{n_p}}$

FETs off, decreasing current:  $t_2 = \frac{1}{2 \cdot f_{switch}} - t_1$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,min} = I_{sec,min} \cdot \frac{n_s}{n_p} - \frac{1}{2} \cdot I_{mag}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

### 17.1.2. Discontinuous Conduction Mode.

FETs on, increasing current:  $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out} + V_f}{2 \cdot f_{switch} \cdot (V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

FETs off, decreasing current:  $t_2 = t_1 \cdot \frac{V_{in} \cdot \frac{n_s}{n_p}}{(V_{out} + V_f)} - t_1$

FETs off, demagnetization:  $t_3 = \frac{1}{2 \cdot f_{switch}} - t_1 - t_2$

Min. Secondary Current:  $I_{sec,min} = 0A$

Max. Secondary Current:  $I_{sec,max} = I_{ripple}$

Min. Primary Current:  $I_{pri,max} = 0A$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

## 17.2. Primary Side Transformer Winding $N_p$

### 17.2.1. CCM & DCM.

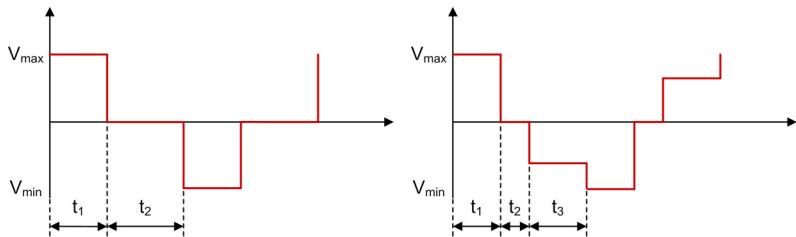


Figure 17.2.1. Full-Bridge - Primary Side Transformer Winding  $N_p$  Voltage Waveforms in CCM and DCM

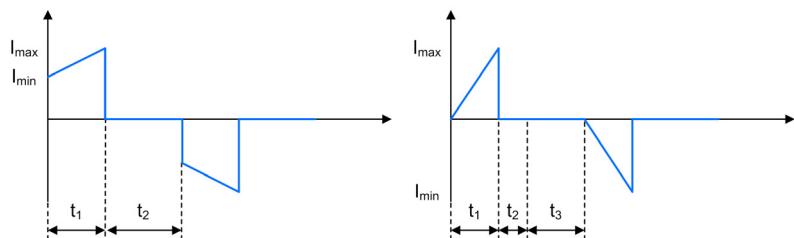


Figure 17.2.2. Full-Bridge - Primary Side Transformer Winding  $N_p$  Current Waveforms in CCM and DCM

Average Primary Transformer Current:  $I_{N_p,avg} = 0A$

Min. Primary Transformer Current:  $I_{N_p,min} = I_{pri,min}$

Max. Primary Transformer Current:  $I_{N_p,max} = I_{pri,max}$

Min. Primary Transformer Voltage:  $V_{N_p,min} = -V_{in}$

Max. Primary Transformer Voltage:  $V_{N_p,max} = V_{in}$

Primary Transformer Voltage during  $t_3$ :  $V_{N_p,t_3} = (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

### 17.3. Secondary Side Transformer Winding $N_{s1}$ & $N_{s2}$

#### 17.3.1. CCM & DCM.

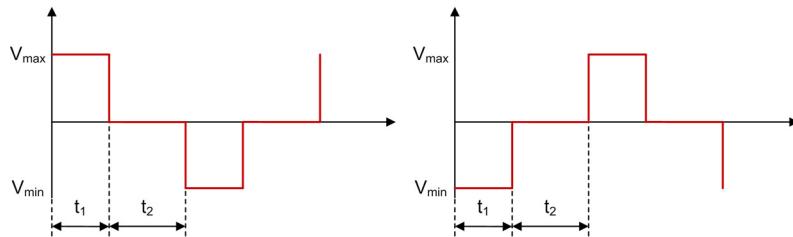


Figure 17.3.1. Full-Bridge - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Voltage Waveforms in CCM

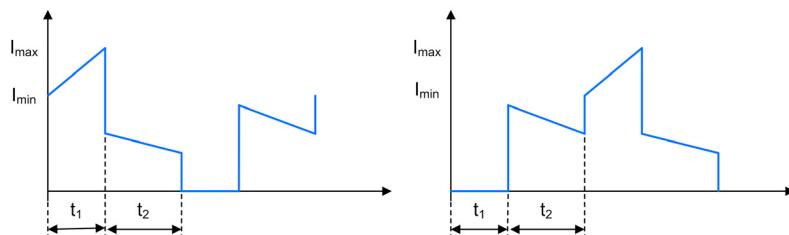


Figure 17.3.2. Full-Bridge - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Current Waveforms in CCM

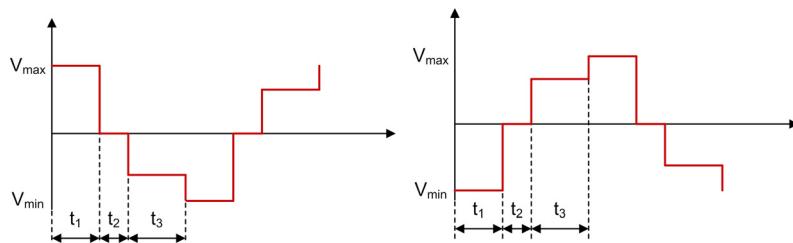


Figure 17.3.3. Full-Bridge - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Voltage Waveforms in DCM

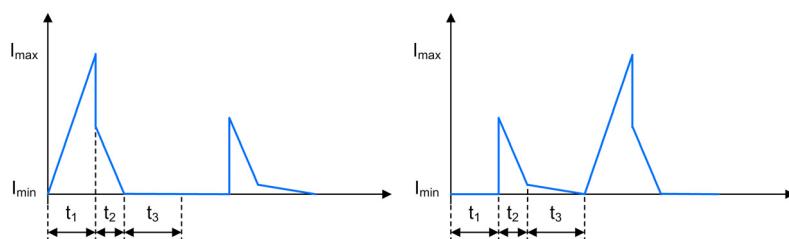


Figure 17.3.4. Full-Bridge - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Current Waveforms in DCM

Min. Secondary Transformer Current ( $t_1$ of FET):	$I_{N_{s1/s2},min} = I_{sec,min}$
Max. Secondary Transformer Current ( $t_2$ of FET):	$I_{N_{s1/s2},max} = I_{sec,max}$
Min. Secondary Transformer Current ( $t_2$ of other FET):	$I_{N_{s1/s2},min,t2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}} - \frac{I_{ripple}}{2}$
Max. Secondary Transformer Current ( $t_2$ of other FET):	$I_{N_{s1/s2},max,t2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}}$
Min. Secondary Transformer Current ( $t_2$ of FET, CCM):	$I_{N_{s1/s2},min,t2} = I_{sec,min} - I_{N_{s1/s2},min,t2,other}$
Min. Secondary Transformer Current ( $t_2$ of FET, DCM):	$I_{N_{s1/s2},min,t2} = 0A$
Max. Secondary Transformer Current ( $t_2$ of FET):	$I_{N_{s1/s2},max,t2} = I_{sec,max} - I_{N_{s1/s2},max,t2,other}$
Min. Secondary Transformer Current ( $t_3$ of other FET):	$I_{N_{s1/s2},min,t3,other} = 0A$
Max. Secondary Transformer Current ( $t_3$ of other FET):	$I_{N_{s1/s2},max,t3,other} = I_{N_{s1/s2},max,t2,other} - I_{trans,sec,max,t2}$
Secondary Transformer Current ( $t_3$ of FET):	$I_{N_{s1/s2},t3} = 0A$
Average Secondary Current:	
$I_{N_{s1/s2},avg} = f_{switch} \cdot \left( \frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 + \frac{I_{N_{s1/s2},max,t2} + I_{N_{s1/s2},min,t2,other}}{2} \cdot t_2 + \frac{I_{N_{s1/s2},min,t2} + I_{N_{s1/s2},max,t2,other}}{2} \cdot t_2 \right)$	
Min. Secondary Transformer Voltage:	$V_{N_{s1/s2},min} = -V_{in} \cdot \frac{n_s}{n_p}$
Max. Secondary Transformer Voltage:	$V_{N_{s1/s2},max} = V_{in} \cdot \frac{n_s}{n_p}$
Secondary Transformer Voltage during $t_3$ :	$V_{N_{s1/s2},max,t3} = -V_{out} - V_f$

## 17.4. Inductor $L_1$

### 17.4.1. CCM & DCM.

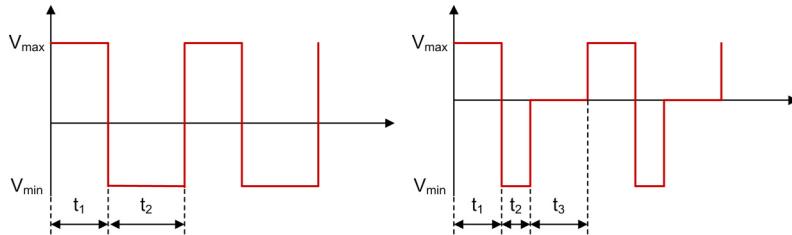


Figure 17.4.1. Full-Bridge - Inductor  $L_1$  Voltage Waveforms in CCM and DCM

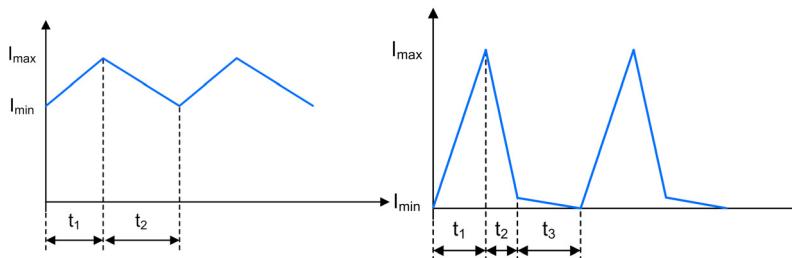


Figure 17.4.2. Full-Bridge - Inductor  $L_1$  Current Waveforms in CCM and DCM

Average Inductor Current:

$$I_{L1,avg} = \frac{I_{sec,max} + I_{sec,min}}{2} \cdot (t_1 + t_2) \cdot f_{switch}$$

Min. Inductor Current:

$$I_{L1,min} = I_{sec,min}$$

Max. Inductor Current:

$$I_{L1,max} = I_{sec,max}$$

Min. Inductor Current during  $t_3$ :

$$I_{L1,min,t_3} = I_{N_{s1/s2},min,t_3}$$

Max. Inductor Current during  $t_3$ :

$$I_{L1,max,t_3} = I_{N_{s1/s2},max,t_3}$$

Min. Inductor Voltage:

$$V_{L1,min} = -V_{out} - V_f$$

Max. Inductor Voltage:

$$V_{L1,max} = V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}$$

Inductor Voltage during  $t_3$ :

$$V_{L1,t_3} = 0V$$

## 17.5. FET $Q_1, Q_2, Q_3$ & $Q_4$

### 17.5.1. CCM & DCM.

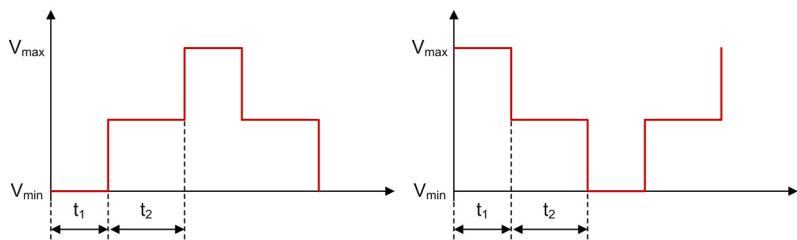


Figure 17.5.1. Full-Bridge - FETs  $Q_1/Q_3$  and  $Q_2/Q_4$  Voltage Waveforms in CCM

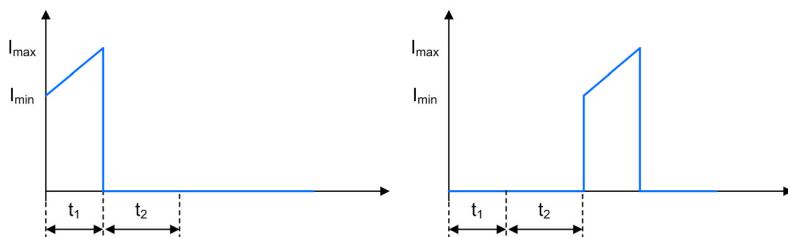


Figure 17.5.2. Full-Bridge - FETs  $Q_1/Q_3$  and  $Q_2/Q_4$  Current Waveforms in CCM

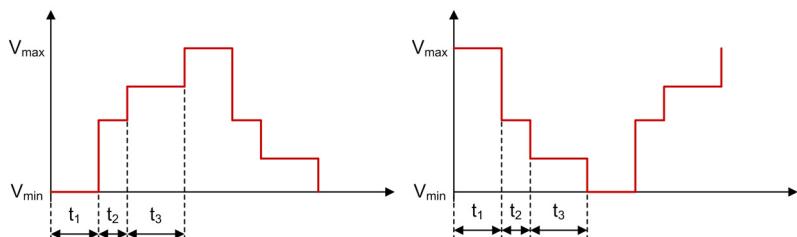


Figure 17.5.3. Full-Bridge - FETs  $Q_1/Q_3$  and  $Q_2/Q_4$  Voltage Waveforms in DCM

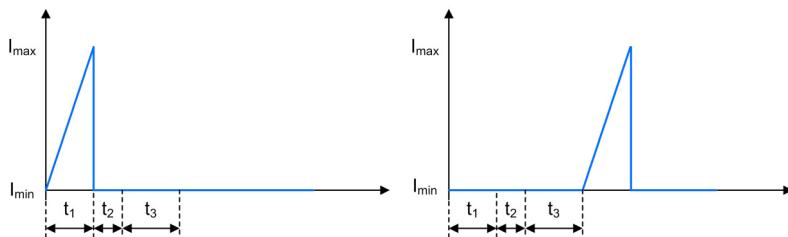


Figure 17.5.4. Full-Bridge - FETs  $Q_1/Q_3$  and  $Q_2/Q_4$  Current Waveforms in DCM

Average FET Current:	$I_{Q_{1/2/3/4},avg} = \frac{I_{pri,min} + I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$
Min. FET Current:	$I_{Q_{1/2/3/4},min} = I_{pri,min}$
Max. FET Current:	$I_{Q_{1/2/3/4},max} = I_{pri,max}$
Min. FET Voltage during $t_1$ :	$V_{Q_{1/2/3/4},min,t_1} = 0V$
Max. FET Voltage during $t_1$ ( $t_1$ of other FET):	$V_{Q_{1/2/3/4},max,t_1} = V_{in}$
FET Voltage during $t_2$ :	$V_{Q_{1/2/3/4},t_2} = \frac{1}{2} \cdot V_{in}$
Min. FET Voltage during $t_3$ ( $t_3$ of other FET):	$V_{Q_{1/2/3/4},min,t_3} = \frac{1}{2} \cdot \left[ V_{in} - (V_{out} + V_f) \cdot \frac{n_p}{n_s} \right]$
Max. FET Voltage during $t_3$ :	$V_{Q_{1/2/3/4},max,t_3} = V_{in} - \frac{1}{2} \cdot \left[ V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s} \right]$

## 17.6. Rectifier Diode $D_1$ & $D_2$

### 17.6.1. CCM & DCM.

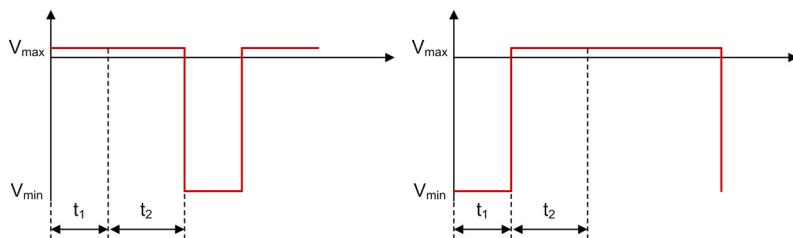


Figure 17.6.1. Full-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in CCM

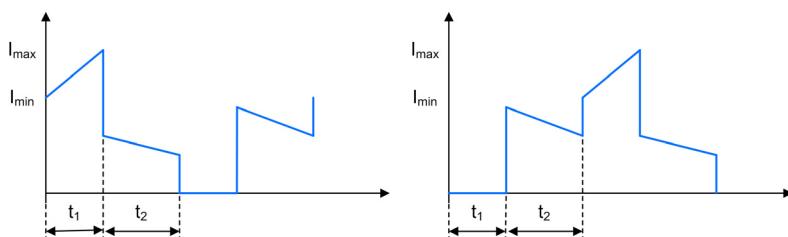


Figure 17.6.2. Full-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in CCM

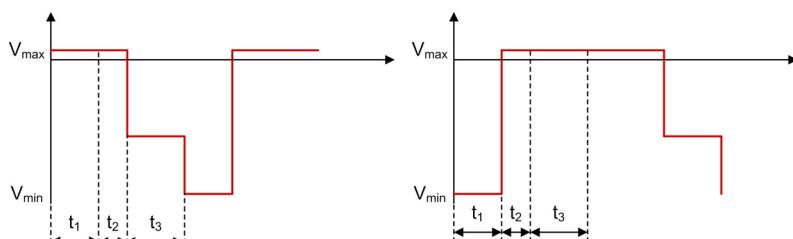


Figure 17.6.3. Full-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in DCM

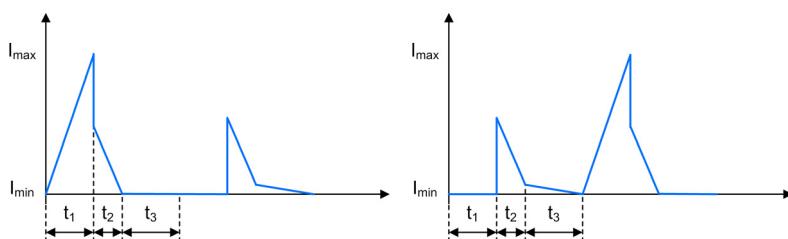


Figure 17.6.4. Full-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in DCM

Average Rectifier Diode Current:	$I_{D_{1/2},avg} = I_{N_{s1/s2},avg}$
Min. Rectifier Diode Current ( $t_1$ of FET):	$I_{D_{1/2},min} = I_{N_{s1/s2},min}$
Max. Rectifier Diode Current ( $t_1$ of FET):	$I_{D_{1/2},max} = I_{N_{s1/s2},max}$
Min. Rectifier Diode Current ( $t_2$ of other FET):	$I_{D_{1/2,min,t2,other}} = I_{N_{s1/s2,min,t2,other}}$
Max. Rectifier Diode Current ( $t_2$ of other FET):	$I_{D_{1/2,max,t2,other}} = I_{N_{s1/s2,max,t2,other}}$
Min. Rectifier Diode Current ( $t_2$ of FET):	$I_{D_{1/2,min,t2}} = I_{N_{s1/s2,min,t2}}$
Max. Rectifier Diode Current ( $t_2$ of FET):	$I_{D_{1/2,max,t2}} = I_{N_{s1/s2,max,t2}}$
Min. Rectifier Diode Current ( $t_3$ of other FET):	$I_{D_{1/2,min,t3,other}} = I_{N_{s1/s2,min,t3}}$
Max. Rectifier Diode Current ( $t_3$ of other FET):	$I_{D_{1/2,max,t3,other}} = I_{N_{s1/s2,max,t3}}$
Rectifier Diode Current ( $t_3$ of FET):	$I_{D_{1/2,t3}} = 0A$
Min. Rectifier Diode Voltage:	$V_{D_{1/2},min} = -2 \cdot V_{in} \cdot \frac{n_s}{n_p} + V_f$
Max. Rectifier Diode Voltage:	$V_{D_{1/2},max} = V_f$
Rectifier Diode Voltage during $t_3$ :	$V_{D_{1/2,t3}} = -2 \cdot V_{out}$

## 17.7. Input Capacitor $C_i$

### 17.7.1. CCM & DCM.

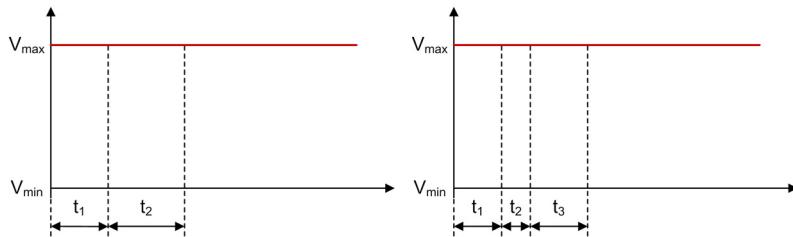


Figure 17.7.1. Full-Bridge - Input Capacitor  $C_i$  Voltage Waveforms in CCM and DCM

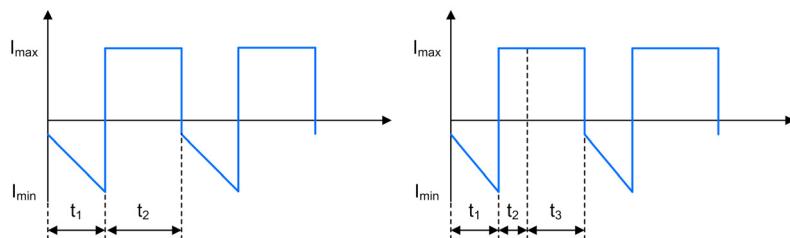


Figure 17.7.2. Full-Bridge - Input Capacitor  $C_i$  Current Waveforms in CCM and DCM

$$\text{Min. Input Capacitor Current during } t_1: \quad I_{C_i,min,t_1} = 2 \cdot I_{Q_{1/2/3/4},avg} - I_{pri,max}$$

$$\text{Max. Input Capacitor Current during } t_1: \quad I_{C_i,max,t_1} = 2 \cdot I_{Q_{1/2/3/4},avg} - I_{pri,min}$$

$$\text{Input Capacitor Current during } t_2 \text{ and } t_3: \quad I_{C_i,t_{2/3}} = 2 \cdot I_{Q_{1/2/3/4},avg}$$

$$\text{Average Input Capacitor Current:} \quad I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage:} \quad V_{C_i} = V_{in}$$

## 17.8. Output Capacitor $C_o$

### 17.8.1. CCM & DCM.

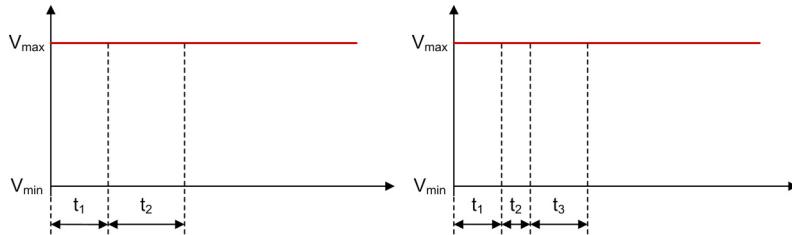


Figure 17.8.1. Full-Bridge - Output Capacitor  $C_o$  Voltage Waveforms in CCM and DCM

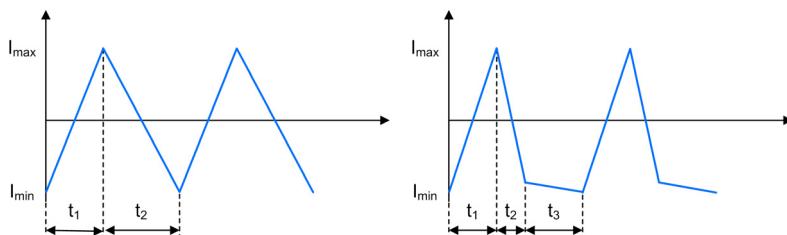


Figure 17.8.2. Full-Bridge - Output Capacitor  $C_o$  Current Waveforms in CCM and DCM

Min. Output Capacitor Current:  $I_{C_o,min} = I_{sec,min} - I_{out}$

Max. Output Capacitor Current:  $I_{C_o,max} = I_{sec,max} - I_{out}$

Min. Output Capacitor Current during  $t_3$ :  $I_{C_o,min,t_3} = I_{sec,min} - I_{out}$

Max. Output Capacitor Current during  $t_3$ :  $I_{C_o,max,t_3} = I_{N_{s1/s2},max,t_3} - I_{out}$

Average Output Capacitor Current:  $I_{C_o,avg} = 0A$

Output Capacitor Voltage:  $V_{C_o} = V_{out}$



# Phase-Shifted Full-Bridge Converter

A Phase-Shifted Full-Bridge regulator converts an input voltage to a higher or lower, positive or negative output voltage level. The energy is transferred to the output when the switches in one leg are both conducting. Calculations are made for Zero Voltage Switching (ZVS) between 50% and 100% load.

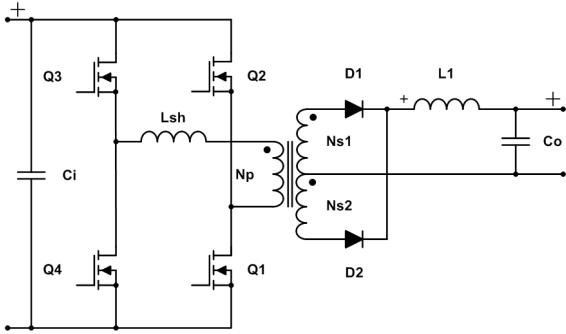


Figure 18.0.1. Schematic of a Phase-Shifted Full-Bridge converter

### 18.1. General

Secondary Side Inductance:

$$L_s = \frac{L_p}{\left(\frac{n_p}{n_s}\right)^2}$$

Voltage across primary Transformer Main Winding:

$$V_{N_p} = V_{in} \cdot \frac{L_p}{L_p + L_{sh}}$$

Inductor Current Ripple:

$$I_{ripple} = \frac{1}{L_1} \cdot (V_{N_p} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot t_1$$

#### 18.1.1. Continuous Conduction Mode.

Duty Cycle Transformer:  $D = \frac{V_{out} + V_f}{V_{N_p} \cdot \frac{n_s}{n_p}}$

The duty cycle of the FETs is 50%.

FETs on, increasing current:  $t_1 = \frac{1}{f_{switch}} \cdot \frac{D}{2}$

FETs off, decreasing current:  $t_2 = \frac{1}{f_{switch}} - t_1$

Phaseshift-time:  $t_3 = \frac{1}{2 \cdot f_{switch}} - t_1$

Magnetization Current:  $I_{mag} = \frac{V_{in} \cdot t_1}{L_p + L_{sh}}$

Min. Secondary Current:  $I_{sec,min} = I_{out} - \frac{1}{2} \cdot I_{ripple}$

Max. Secondary Current:  $I_{sec,max} = I_{out} + \frac{1}{2} \cdot I_{ripple}$

Min. Primary Current:  $I_{pri,min} = I_{sec,min} \cdot \frac{n_s}{n_p} - \frac{1}{2} \cdot I_{mag}$

Max. Primary Current:  $I_{pri,max} = I_{sec,max} \cdot \frac{n_s}{n_p} + \frac{1}{2} \cdot I_{mag}$

Average Input Current:  $I_{in,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}}$

## 18.2. Primary Side Transformer Winding $N_p$

### 18.2.1. CCM.

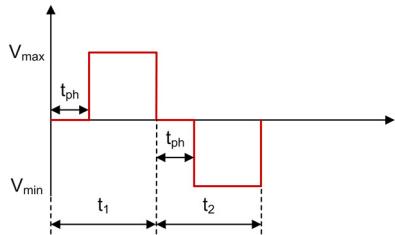


Figure 18.2.1. Phase-Shifted Full-Bridge - Primary Side Transformer Winding  $N_p$  Voltage Waveform in CCM

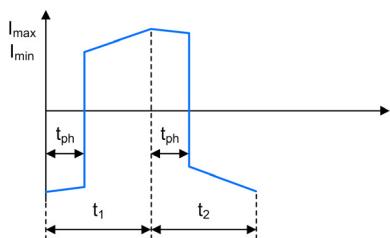


Figure 18.2.2. Phase-Shifted Full-Bridge - Primary Side Transformer Winding  $N_p$  Current Waveform in CCM

Average Primary Transformer Current:  $I_{N_p,avg} = 0A$

Min. Primary Transformer Current:  $I_{N_p,min} = I_{pri,min}$

Max. Primary Transformer Current:  $I_{N_p,max} = I_{pri,max}$

Primary Transformer Current (freewheeling):  $I_{N_p,min,fw} = I_{N_p,max} - \frac{I_{ripple}}{2 \cdot \frac{n_p}{n_s}}$

Min. Primary Transformer Voltage:  $V_{N_p,min} = -V_{N_p}$

Max. Primary Transformer Voltage:  $V_{N_p,max} = V_{N_p}$

### 18.3. Secondary Side Transformer Winding $N_{s1}$ & $N_{s2}$

#### 18.3.1. CCM.

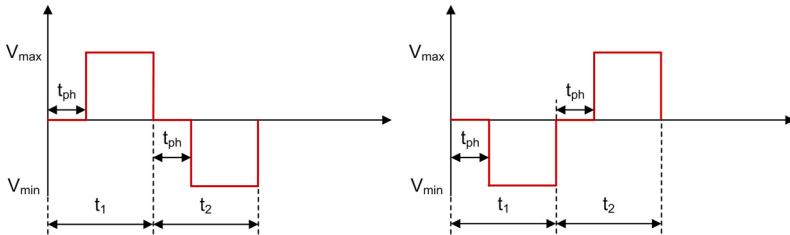


Figure 18.3.1. Phase-Shifted Full-Bridge - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Voltage Waveforms in CCM

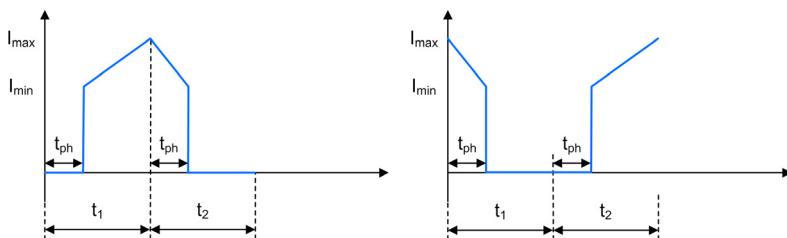


Figure 18.3.2. Phase-Shifted Full-Bridge - Secondary Side Transformer Windings  $N_{s1}$  and  $N_{s2}$  Current Waveforms in CCM

Min. Secondary Transformer Current:  $I_{N_{s1/s2},min} = I_{sec,min}$

Max. Secondary Transformer Current:  $I_{N_{s1/s2},max} = I_{sec,max}$

Average Secondary Transformer Current:

$$I_{N_{s1/s2},avg} = f_{switch} \cdot \left( \frac{I_{N_{s1/s2},min} + I_{N_{s1/s2},max}}{2} \cdot (t_1 - t_{ph}) + \frac{I_{N_{s1/s2},max} + I_{N_{s1/s2},min}}{2} \cdot t_{ph} \right)$$

Min. Secondary Transformer Voltage:  $V_{N_{s1/s2},min} = -V_{N_p} \cdot \frac{n_s}{n_p}$

Max. Secondary Transformer Voltage:  $V_{N_{s1/s2},max} = V_{N_p} \cdot \frac{n_s}{n_p}$

## 18.4. Inductor $L_1$

### 18.4.1. CCM.

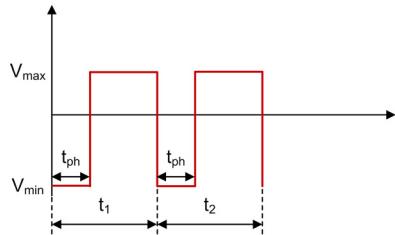


Figure 18.4.1. Phase-Shifted Full-Bridge - Inductor  $L_1$  Voltage Waveform in CCM

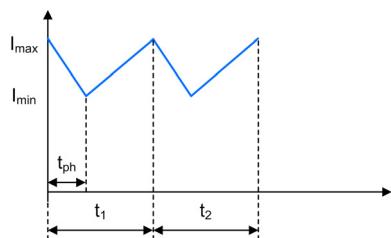


Figure 18.4.2. Phase-Shifted Full-Bridge - Inductor  $L_1$  Current Waveform in CCM

$$\text{Average Inductor Current: } I_{L_1,\text{avg}} = \frac{I_{\text{sec},\text{max}} + I_{\text{sec},\text{min}}}{2}$$

$$\text{Min. Inductor Current: } I_{L_1,\text{min}} = I_{\text{sec},\text{min}}$$

$$\text{Max. Inductor Current: } I_{L_1,\text{max}} = I_{\text{sec},\text{max}}$$

$$\text{Min. Inductor Voltage: } V_{L_1,\text{min}} = -V_{\text{out}} - V_f$$

$$\text{Max. Inductor Voltage: } V_{L_1,\text{max}} = V_{\text{in}} \cdot \frac{n_s}{n_p} - V_f - V_{\text{out}}$$

## 18.5. FET $Q_1$ , $Q_2$ , $Q_3$ & $Q_4$

### 18.5.1. CCM.

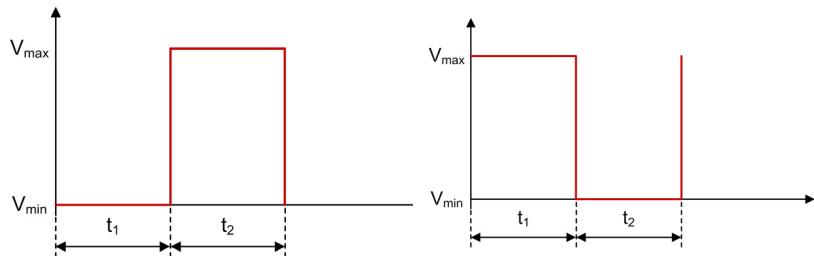


Figure 18.5.1. Phase-Shifted Full-Bridge - FETs  $Q_1$  and  $Q_2$  Voltage Waveforms in CCM

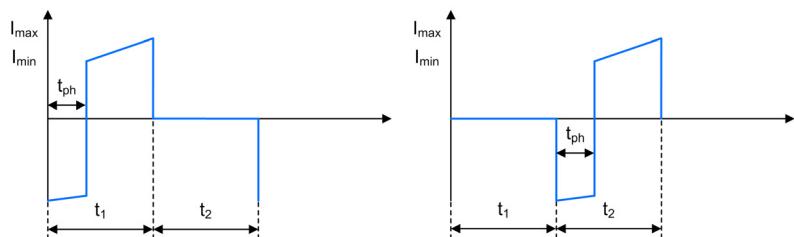


Figure 18.5.2. Phase-Shifted Full-Bridge - FETs  $Q_1$  and  $Q_2$  Current Waveforms in CCM

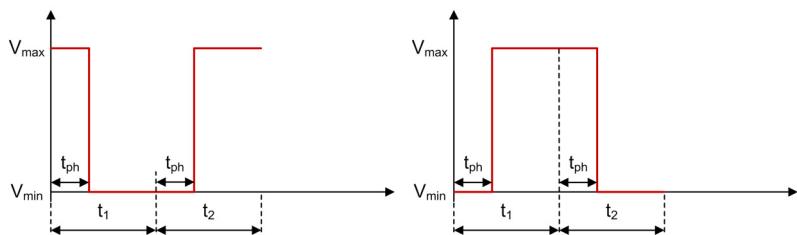


Figure 18.5.3. Phase-Shifted Full-Bridge - FETs  $Q_3$  and  $Q_4$  Voltage Waveforms in CCM

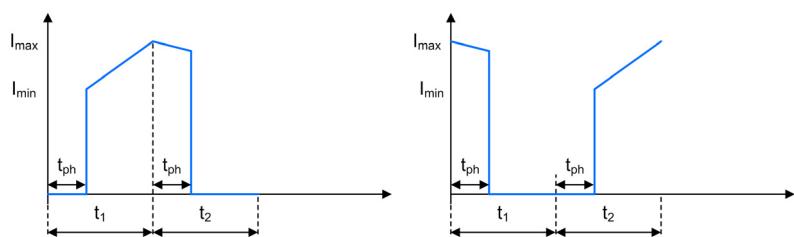


Figure 18.5.4. Phase-Shifted Full-Bridge - FETs  $Q_3$  and  $Q_4$  Current Waveforms in CCM

Min. FET Current ( $t_1$  of FET, all FETs):  $I_{Q_{1/2/3/4},min} = I_{pri,min}$

Max. FET Current ( $t_1$  of FET, all FETs):  $I_{Q_{1/2/3/4},max} = I_{pri,max}$

Min. FET Current (freewheeling,  $Q_3$  &  $Q_4$ ):  $I_{Q_{3/4},min,t_{ph}} = I_{N_p,min}$

Max. FET Current (freewheeling,  $Q_3$  &  $Q_4$ ):  $I_{Q_{3/4},max,t_{ph}} = I_{N_p,max}$

Min. FET Current (freewheeling,  $Q_1$  &  $Q_2$ ):  $I_{Q_{1/2},min,t_{ph}} = -I_{N_p,max}$

Max. FET Current (freewheeling,  $Q_1$  &  $Q_2$ ):  $I_{Q_{1/2},max,t_{ph}} = -I_{N_p,min}$

Average FET Current ( $Q_3$  &  $Q_4$ ):

$$I_{Q_{3/4},avg} = \left( \frac{I_{Q_{1/2/3/4},min} + I_{Q_{1/2/3/4},max}}{2} \cdot (t_1 - t_{ph}) + \frac{I_{Q_{3/4},min,t_{ph}} + I_{Q_{3/4},max,t_{ph}}}{2} \cdot t_{ph} \right) \cdot f_{switch}$$

Average FET Current ( $Q_1$  &  $Q_2$ ):

$$I_{Q_{1/2},avg} = \left( \frac{I_{Q_{1/2/3/4},min} + I_{Q_{1/2/3/4},max}}{2} \cdot (t_1 - t_{ph}) + \frac{I_{Q_{1/2},min,t_{ph}} + I_{Q_{1/2},max,t_{ph}}}{2} \cdot t_{ph} \right) \cdot f_{switch}$$

Min. FET Voltage:  $V_{Q_{1/2/3/4},min} = 0V$

Max. FET Voltage:  $V_{Q_{1/2/3/4},max} = V_{in}$

## 18.6. Rectifier Diodes $D_1$ & $D_2$

### 18.6.1. CCM.

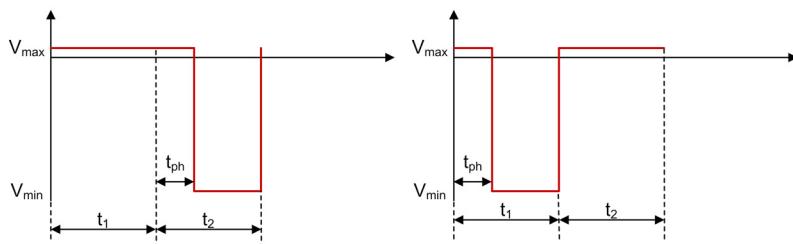


Figure 18.6.1. Phase-Shifted Full-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Voltage Waveforms in CCM

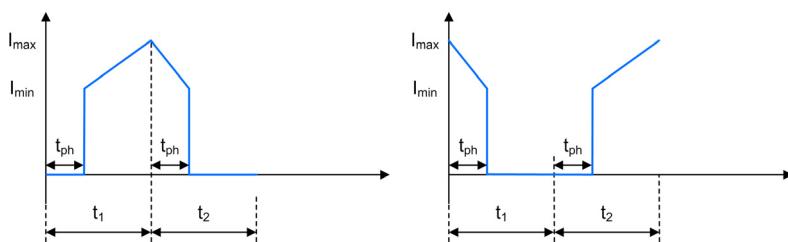


Figure 18.6.2. Phase-Shifted Full-Bridge - Rectifier Diodes  $D_1$  and  $D_2$  Current Waveforms in CCM

Average Rectifier Diode Current:  $I_{D_{1/2},avg} = I_{N_{s1/s2},avg}$

Min. Rectifier Diode Current:  $I_{D_{1/2},min} = I_{N_{s1/s2},min}$

Max. Rectifier Diode Current:  $I_{D_{1/2},max} = I_{N_{s1/s2},max}$

Min. Rectifier Diode Voltage:  $V_{D_{1/2},min} = -2 \cdot V_{N_p} \cdot \frac{n_s}{n_p} + V_f$

Max. Rectifier Diode Voltage:  $V_{D_{1/2},max} = V_f$

## 18.7. Input Capacitor $C_i$

### 18.7.1. CCM.

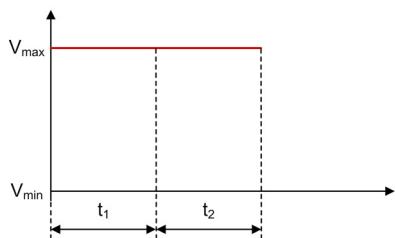


Figure 18.7.1. Phase-Shifted Full-Bridge - Input Capacitor  $C_i$  Voltage Waveform in CCM

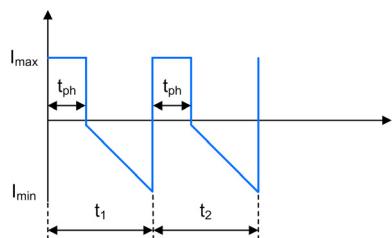


Figure 18.7.2. Phase-Shifted Full-Bridge - Input Capacitor  $C_i$  Current Waveform in CCM

$$\text{Min. Input Capacitor Current during } t_1: \quad I_{C_i,min,t_1} = 2 \cdot I_{in,avg} - I_{N_p,max}$$

$$\text{Max. Input Capacitor Current during } t_1: \quad I_{C_i,max,t_1} = 2 \cdot I_{in,avg} - I_{N_p,min}$$

$$\text{Input Capacitor Current during } t_2: \quad I_{C_i,t_2} = 2 \cdot I_{in,avg}$$

$$\text{Average Input Capacitor Current:} \quad I_{C_i,avg} = 0A$$

$$\text{Input Capacitor Voltage:} \quad V_{C_i} = V_{in}$$

## 18.8. Output Capacitor $C_o$

### 18.8.1. CCM.

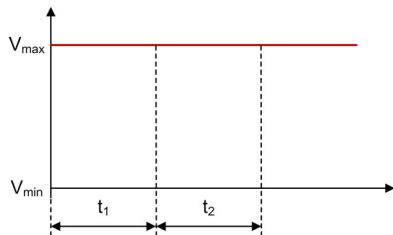


Figure 18.8.1. Phase-Shifted Full-Bridge - Output Capacitor  $C_o$  Voltage Waveform in CCM

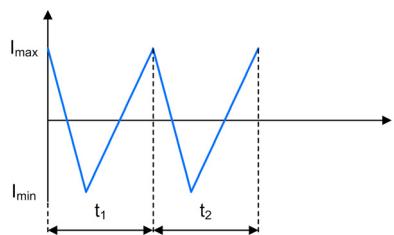


Figure 18.8.2. Phase-Shifted Full-Bridge - Output Capacitor  $C_o$  Current Waveform in CCM

Min. Output Capacitor Current:  $I_{C_o,min} = I_{out} - I_{sec,max}$

Max. Output Capacitor Current:  $I_{C_o,max} = I_{out} - I_{sec,min}$

Average Output Capacitor Current:  $I_{C_o,avg} = 0A$

Output Capacitor Voltage:  $V_{C_o} = V_{out}$

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