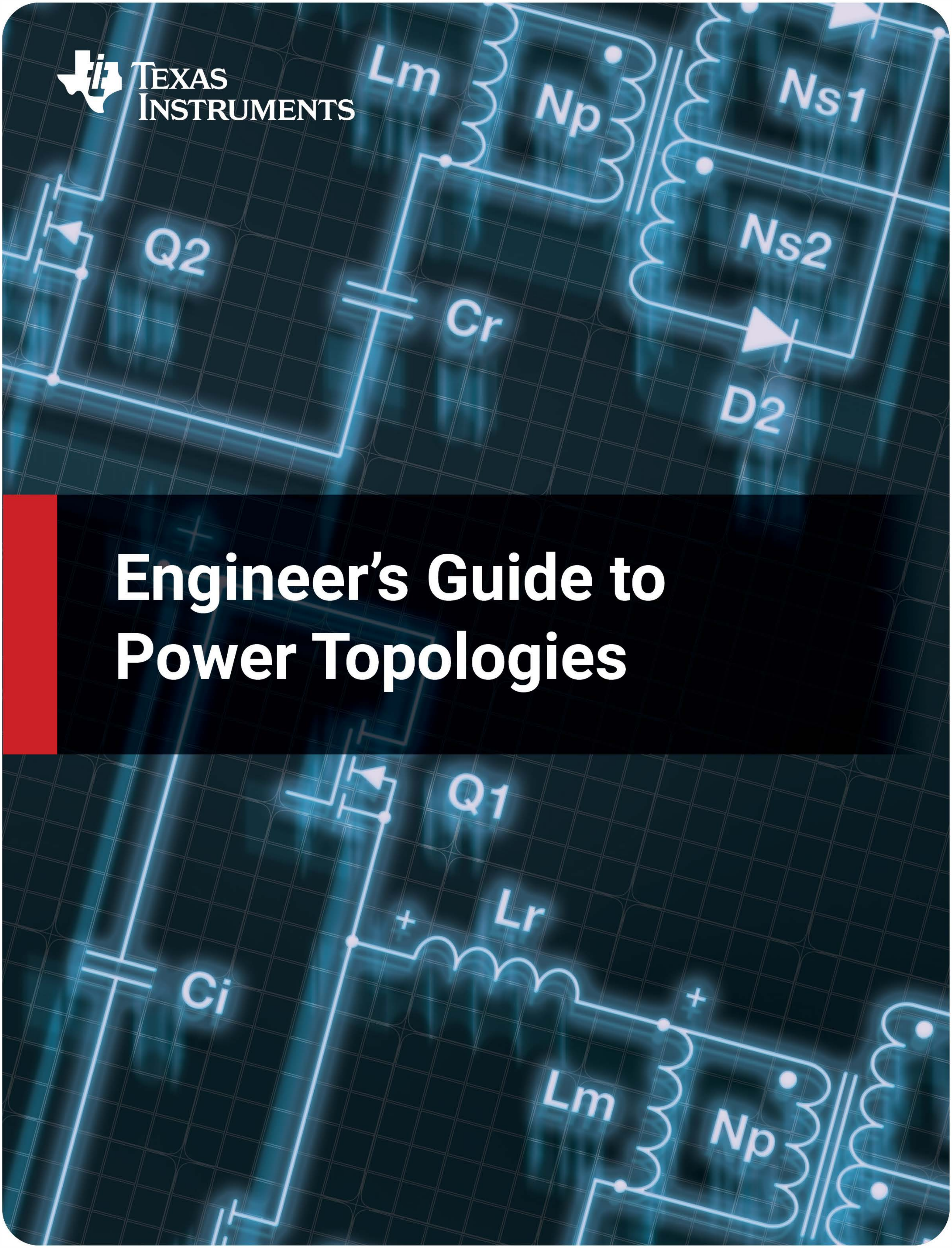
Texas Instruments

Engineer’s Guide to Power Topologies



Contents

CHAPTER 1

Abbrevations and General Information

Expression	Abbrevation
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 td and t1 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-sychronous 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.

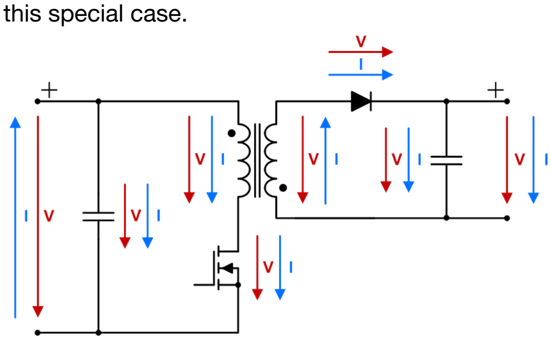


Figure 1.0.1.**Example of how the waveforms of a Flyback converter are displayed.**

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.

CHAPTER 2

General Equations for Calculating RMS and AC Currents

2.1. Positive triangular waveforms without offset

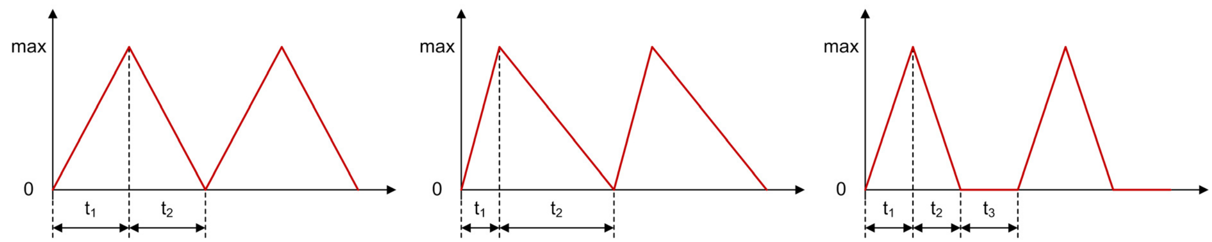


Figure 2.1.1. **Positive triangular waveforms without offset**

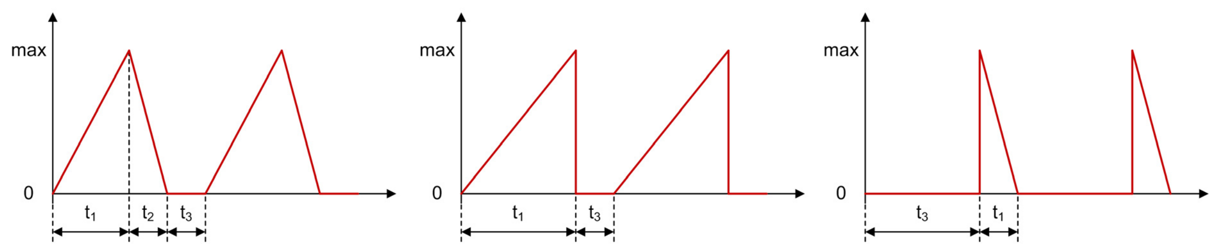


Figure 2.1.2. **Positive triangular waveforms without offset**

Average:

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

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

RMS:

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

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

AC:

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

2.2. Positive triangular waveforms with offset

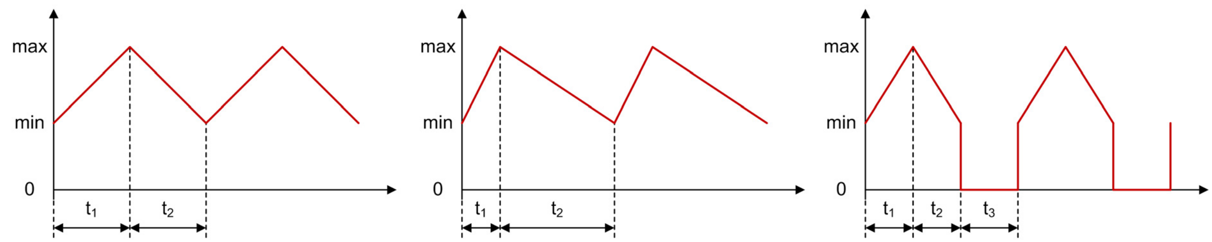


Figure 2.2.1. **Positive triangular waveforms with offset**

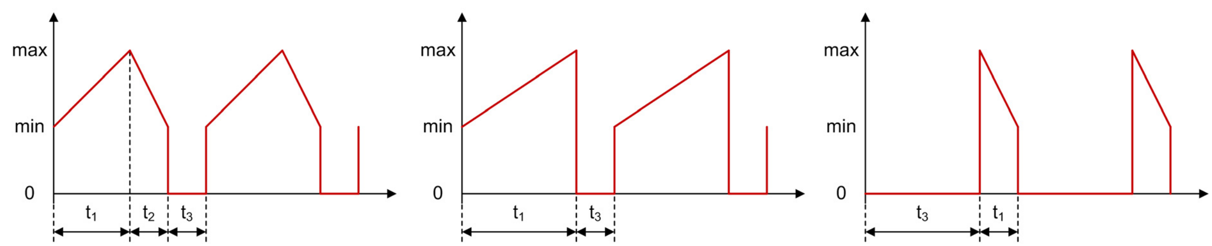


Figure 2.2.2. **Positive triangular waveforms with offset**

Average:

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

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

RMS:

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

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

AC:

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

2.3. Positive and negative triangular waveforms without offset

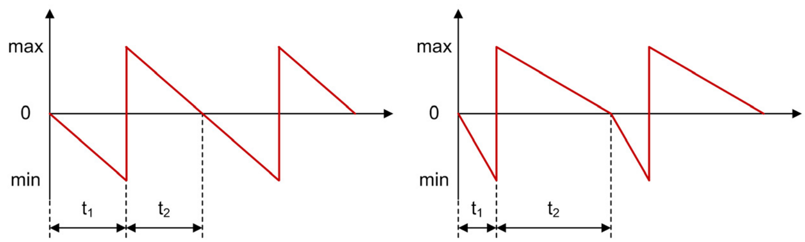


Figure 2.3.1. **Positive and negative triangular waveforms without offset**

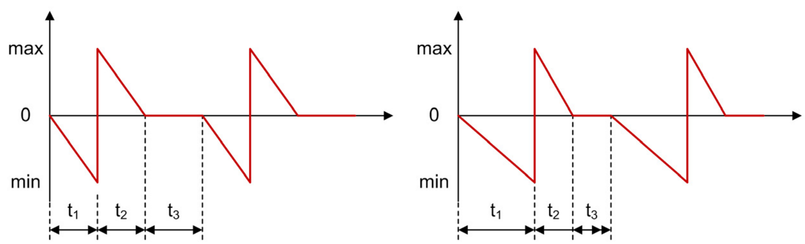


Figure 2.3.2. **Positive and negative triangular waveforms without offset**

Average:

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

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

RMS:

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

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

AC:

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

2.4. Positive and negative triangular waveforms with offset

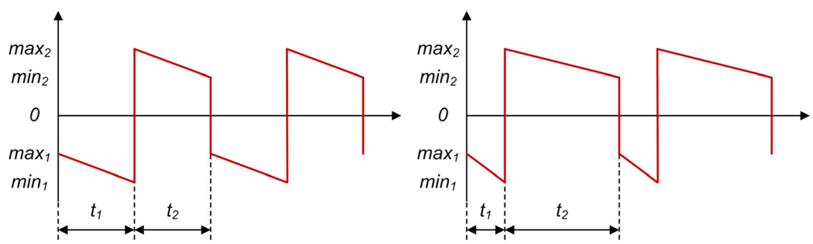


Figure 2.4.1. **Positive and negative triangular waveforms with offset**

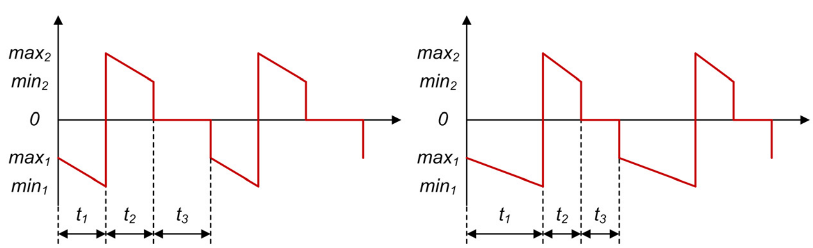


Figure 2.4.2. **Positive and negative triangular waveforms with offset**

Average:

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

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

RMS:

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

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

AC:

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

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

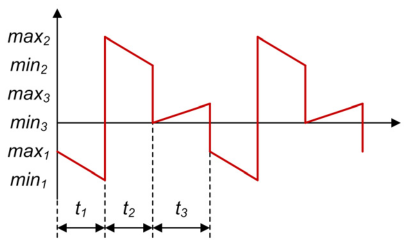


Figure 2.5.1. **Positive and negative triangular waveforms with offset**

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:

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

AC:

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

CHAPTER 3

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.

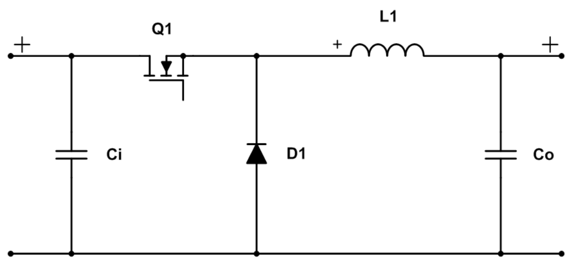


Figure 3.0.1. **Schematic of a non-synchronous Buck converter**

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.

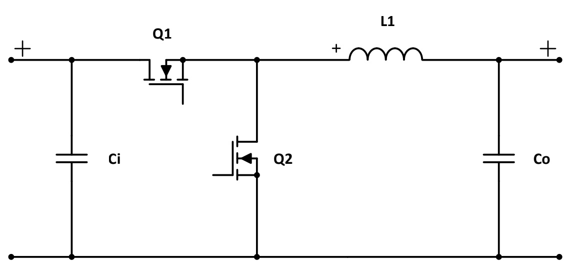


Figure 3.0.2. **Schematic of a synchronous Buck converter**

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.

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

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

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

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

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.

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

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

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

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

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

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.

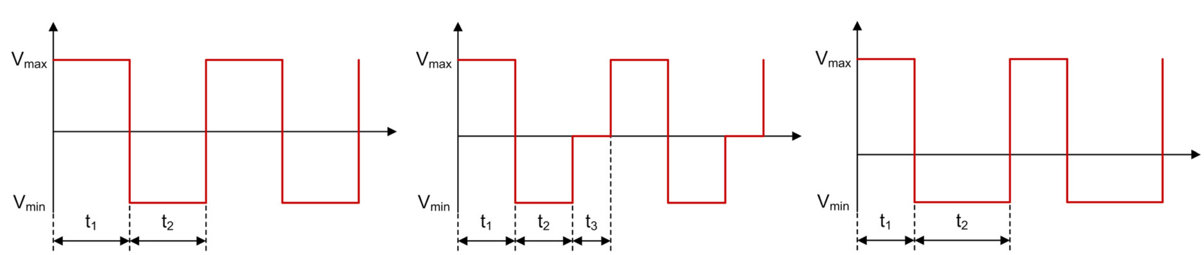


Figure 3.2.1. **Buck - Inductor L_1 Voltage Waveforms in CCM, DCM and synchronous forced PWM**

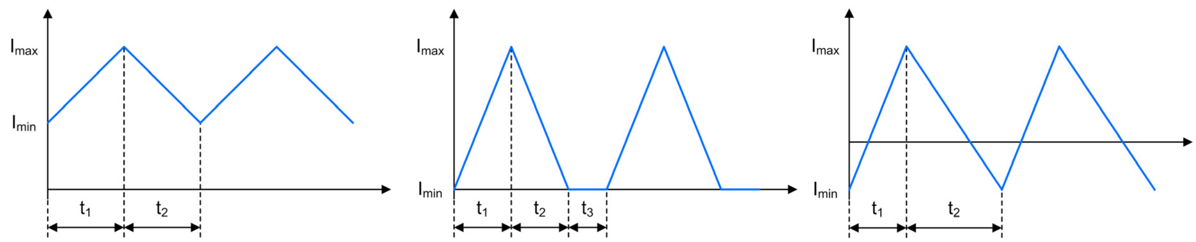


Figure 3.2.2. **Buck - Inductor L_1 Current Waveforms in CCM, DCM and synchronous forced PWM**

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

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

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

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

3.3. FET Q_1

3.3.1. CCM, DCM & Synchronous forced PWM.

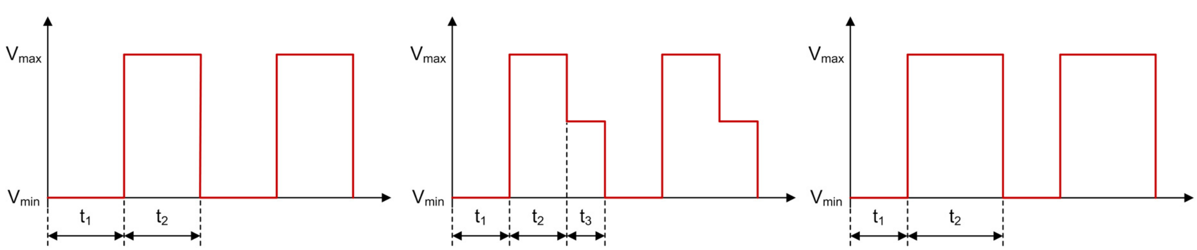


Figure 3.3.1. **Buck - FET Q_1 Voltage Waveforms in CCM, DCM and synchronous forced PWM**

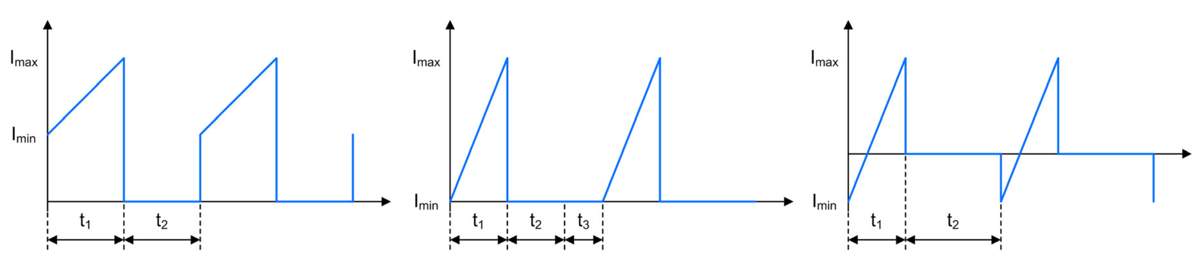


Figure 3.3.2. **Buck - FET Q_1 Current Waveforms in CCM, DCM and synchronous forced PWM**

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.

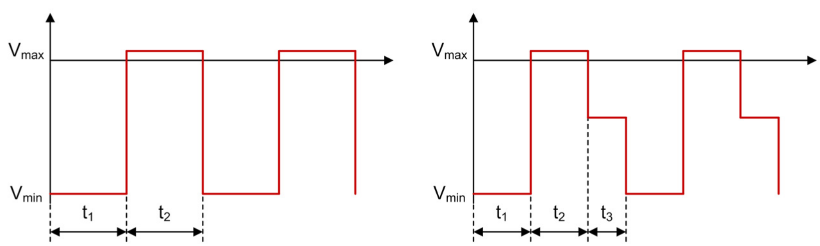


Figure 3.4.1. **Buck - Diode D_1 Voltage Waveforms in CCM and DCM**

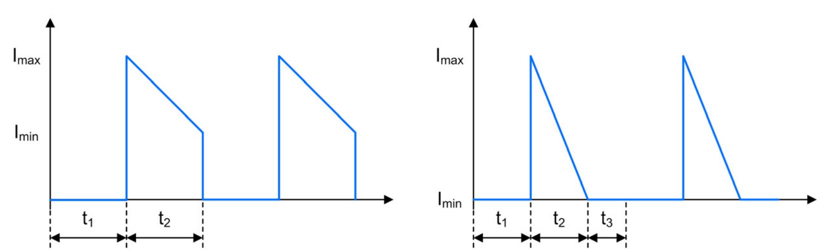


Figure 3.4.2. **Buck - Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

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

3.4.2. Synchronous Rectifier FET Q_2 - forced PWM.

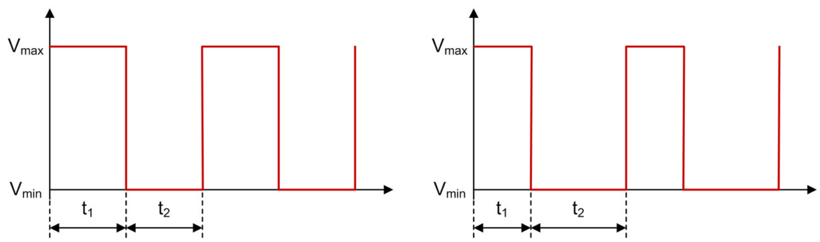


Figure 3.4.3. **Synchronous Buck - Synchronous Rectifier FET Q_2 Voltage Waveforms in CCM and forced PWM mode**

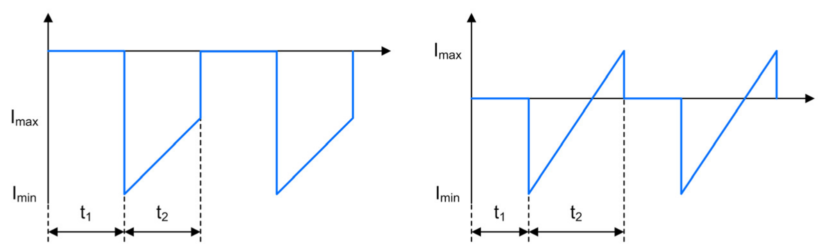


Figure 3.4.4. **Synchronous Buck - Synchronous Rectifier FET Q_2 Current Waveforms in CCM and forced PWM mode**

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.

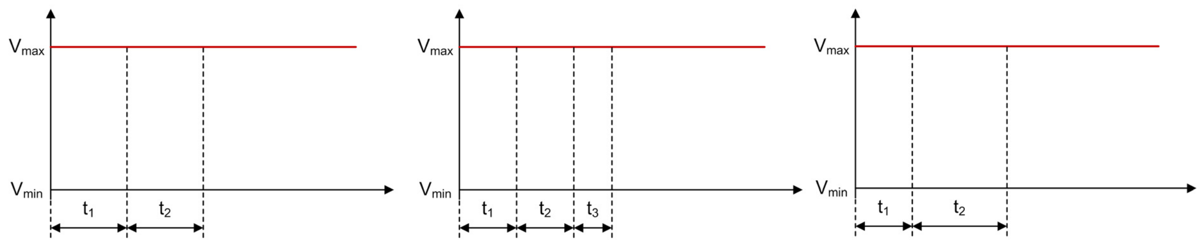


Figure 3.5.1. **Buck - Input Capacitor C_i Voltage Waveforms in CCM, DCM and synchronous forced PWM**

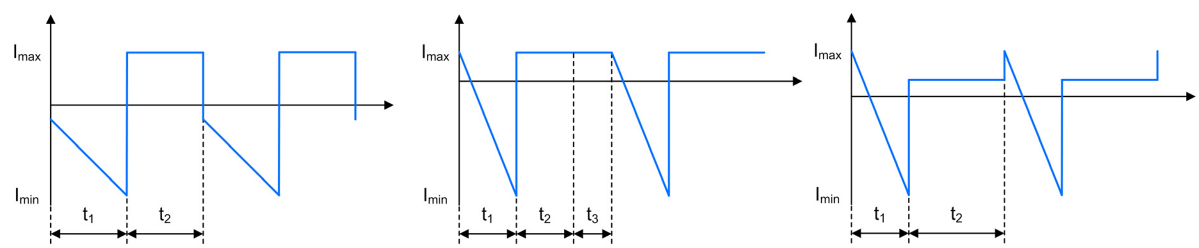


Figure 3.5.2. **Buck - Input Capacitor C_i Current Waveforms in CCM, DCM and synchronous forced PWM**

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.

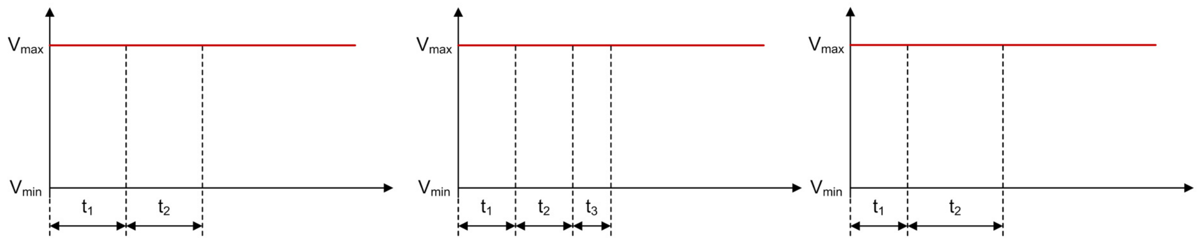


Figure 3.6.1. **Buck - Output Capacitor C_o Voltage Waveforms in CCM, DCM and synchro-nous forced PWM**

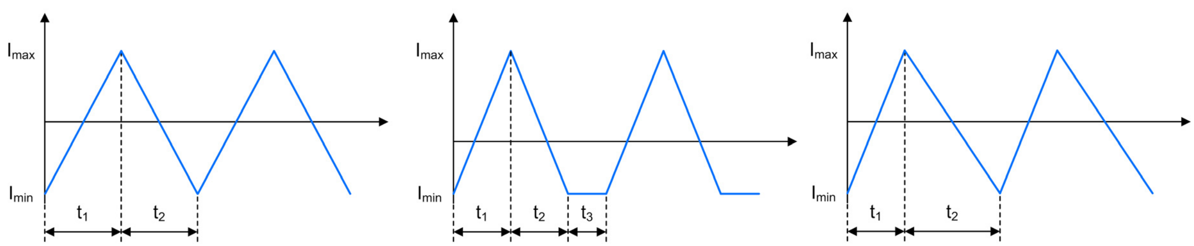


Figure 3.6.2. **Buck - Output Capacitor C_o Current Waveforms in CCM, DCM and synchro-nous forced PWM**

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

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

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

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

CHAPTER 4

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.

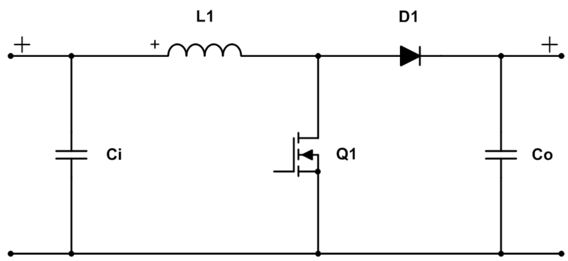


Figure 4.0.1. **Schematic of a Boost converter**

4.1. General

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

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

4.1.1. CCM.

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

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

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

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

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

4.1.2. DCM.

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

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

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

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

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

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

4.2. Inductor L_1

4.2.1. CCM & DCM.

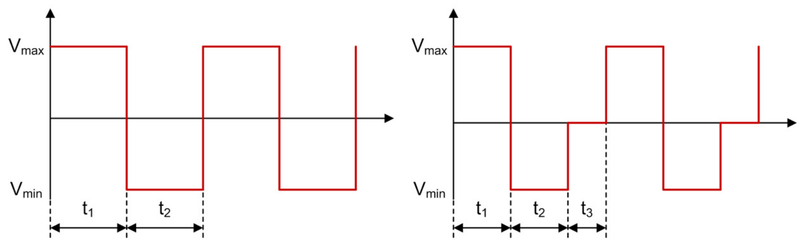


Figure 4.2.1. **Boost - Inductor L_1 Voltage Waveforms in CCM and DCM**

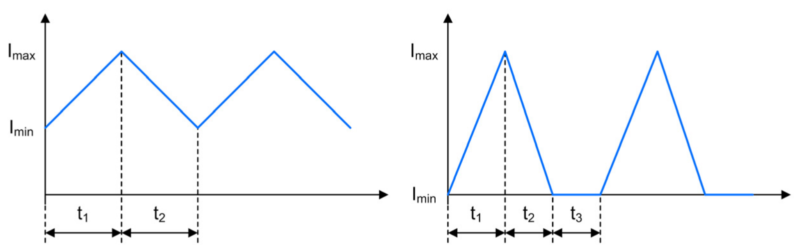


Figure 4.2.2. **Boost - Inductor L_1 Current Waveforms in CCM and DCM**

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

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

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

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

4.3. FET Q_1

4.3.1. CCM & DCM.

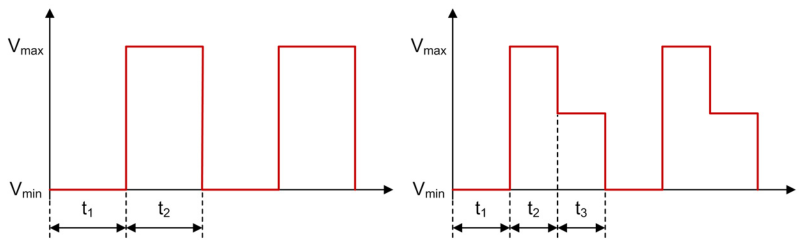


Figure 4.3.1. **Boost - FET Q_1 Voltage Waveforms in CCM and DCM**

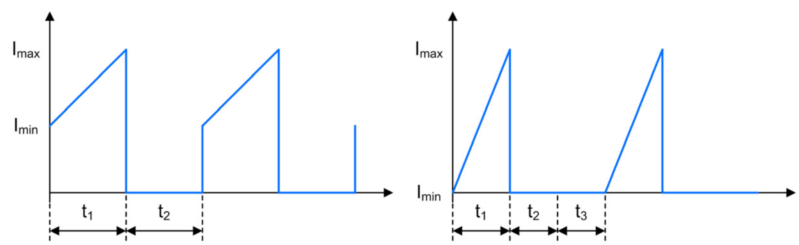


Figure 4.3.2. **Boost - FET Q_1 Current Waveforms in CCM and DCM**

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

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

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

FET Voltage during t_3: $\mathrm{V}_{Q_1,t_3} = V_{in}$

4.4. Diode D_1

4.4.1. CCM & DCM.

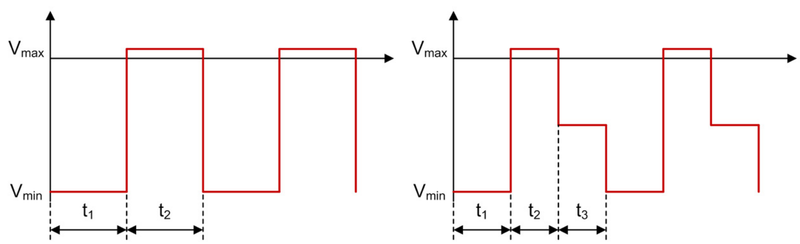


Figure 4.4.1. **Boost - Diode D_1 Voltage Waveforms in CCM and DCM**

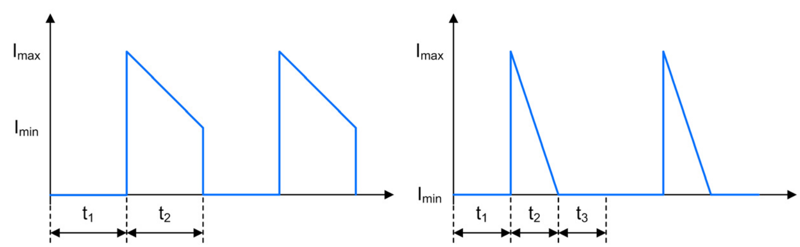


Figure 4.4.2. **Boost - Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

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

4.5. Input Capacitor C_i

4.5.1. CCM & DCM.

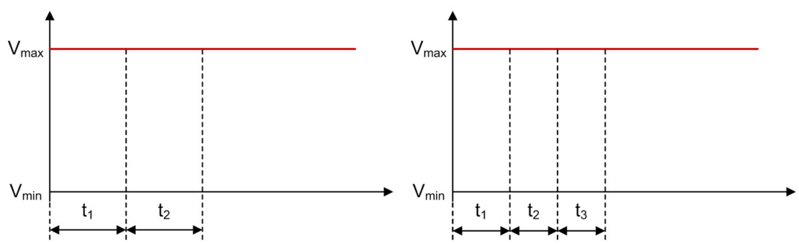


Figure 4.5.1. **Boost - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

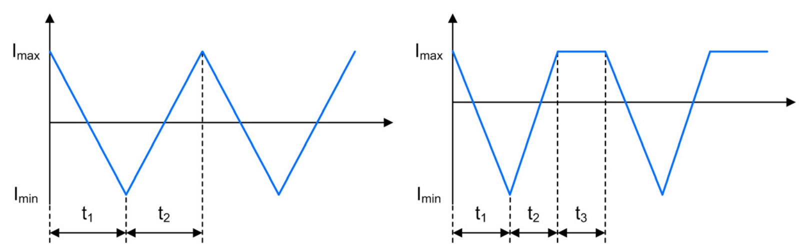


Figure 4.5.2. **Boost - Input Capacitor C_i Current Waveforms in CCM and DCM**

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

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

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

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

4.6. Output Capacitor C_o

4.6.1. CCM & DCM.

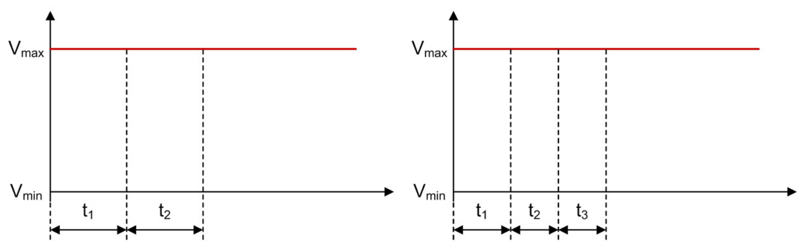


Figure 4.6.1. **Boost - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

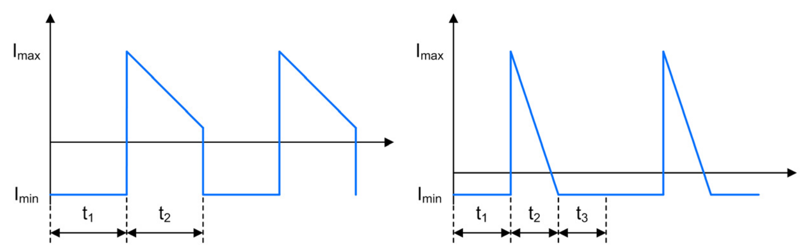


Figure 4.6.2. **Boost - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

CHAPTER 5

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.

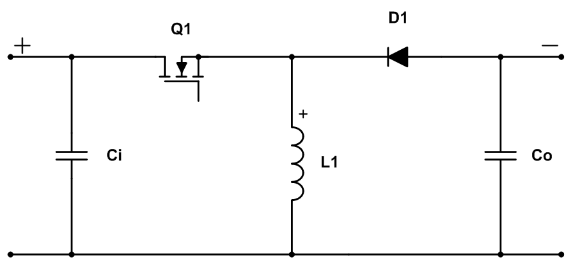


Figure 5.0.1. **Schematic of an Inverting Buck-Boost converter**

5.1. General

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

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

5.1.1. CCM.

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

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

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

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

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.

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

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

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

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

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

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.

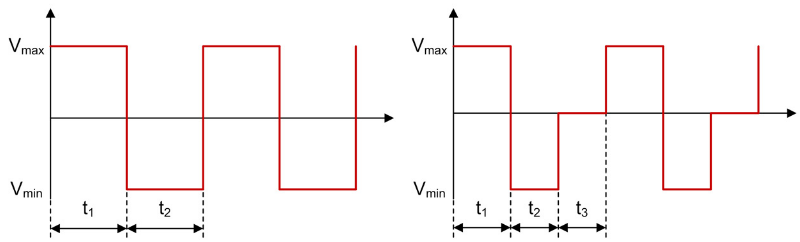


Figure 5.2.1. **Inverting Buck Boost - Inductor L_1 Voltage Waveforms in CCM and DCM**

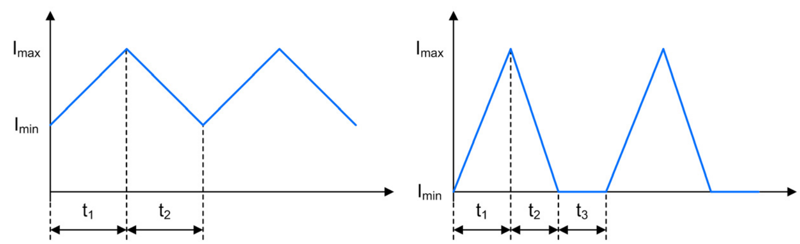


Figure 5.2.2. **Inverting Buck Boost - Inductor L_1 Current Waveforms in CCM and DCM**

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.

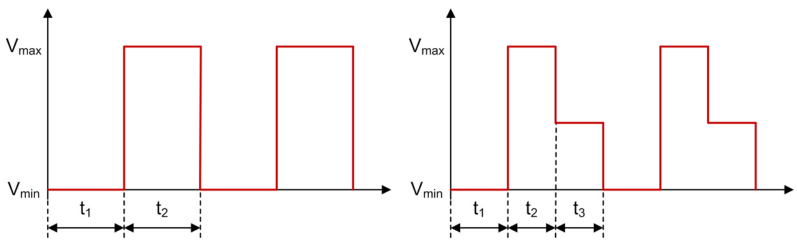


Figure 5.3.1. **Inverting Buck Boost - FET Q_1 Voltage Waveforms in CCM and DCM**

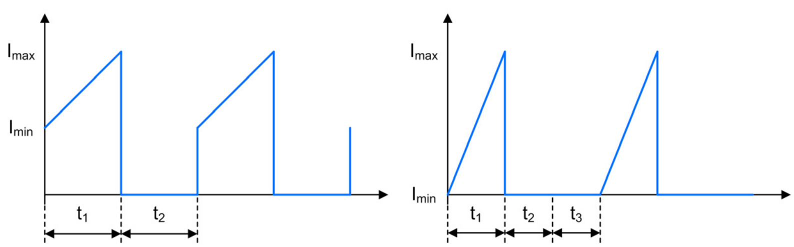


Figure 5.3.2. **Inverting Buck Boost - FET Q_1 Current Waveforms in CCM and DCM**

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: $\mathrm{V}_{Q_1,t_3} = V_{in}$

5.4. Diode D_1

5.4.1. CCM & DCM.

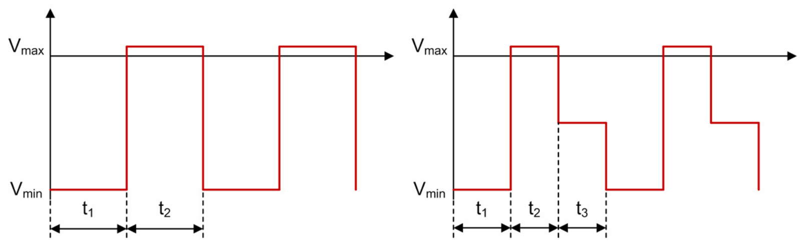


Figure 5.4.1. **Inverting Buck Boost - Diode D_1 Voltage Waveforms in CCM and DCM**

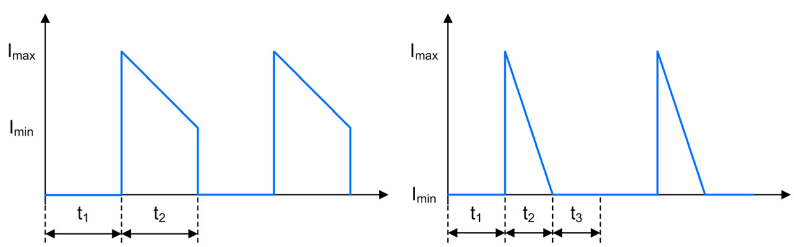


Figure 5.4.2. **Inverting Buck Boost - Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

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

5.5. Input Capacitor C_i

5.5.1. CCM & DCM.

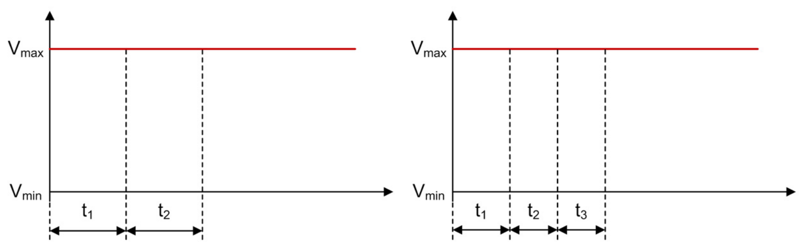


Figure 5.5.1. **Inverting Buck Boost - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

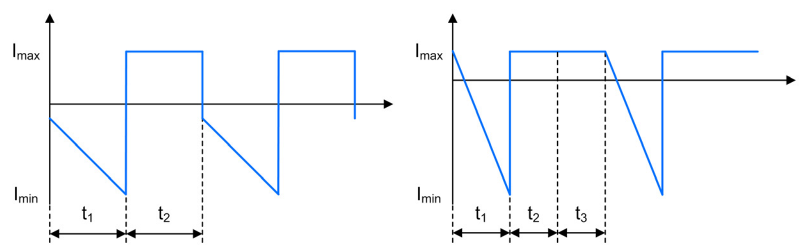


Figure 5.5.2. **Inverting Buck Boost - Input Capacitor C_i Current Waveforms in CCM and DCM**

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

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

Input Capacitor current during t_2 and t_3: $\mathrm{I}_{C_i,t_{2/3}} = \mathrm{I}_{in}$

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

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

5.6. Output Capacitor C_o

5.6.1. CCM & DCM.

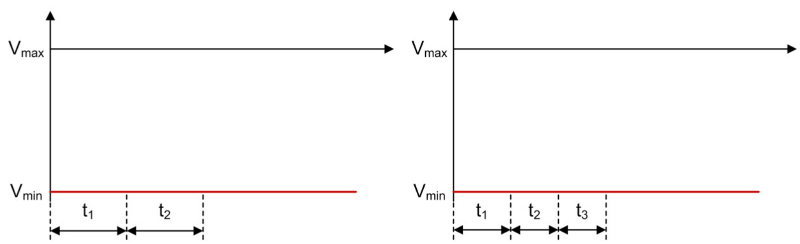


Figure 5.6.1. **Inverting Buck Boost - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

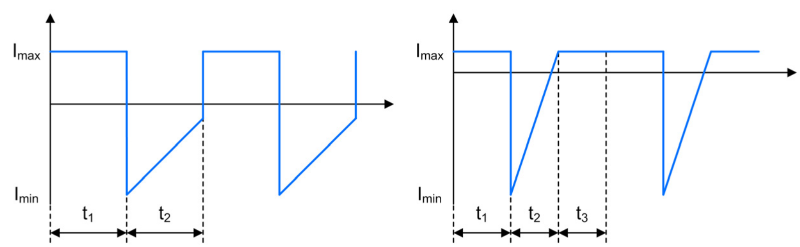


Figure 5.6.2. **Inverting Buck Boost - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

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.

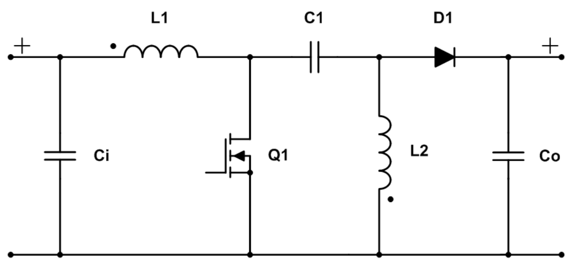


Figure 6.0.1. **Schematic of a SEPIC converter**

6.1. General

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.

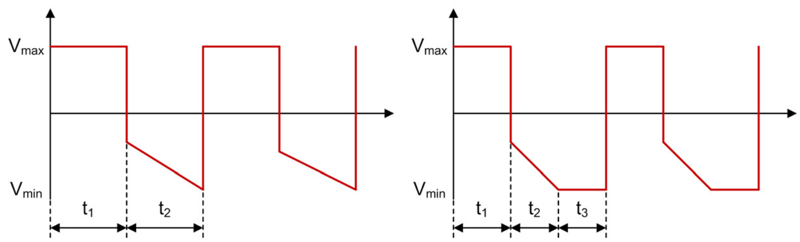


Figure 6.2.1. **SEPIC - Inductor L_1 Voltage Waveforms in CCM and DCM**

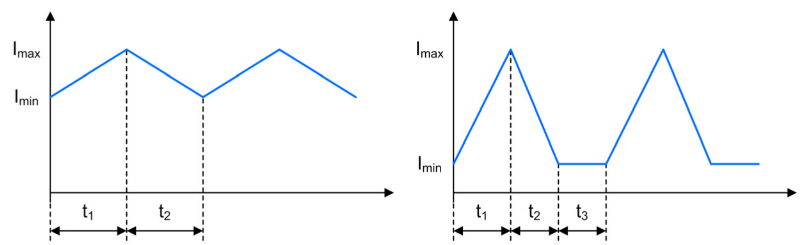


Figure 6.2.2. **SEPIC - Inductor L_1 Current Waveforms in CCM and DCM**

Min. Inductor Current: $I_{L_1,min} = I_{in,avg} - \frac{1}{2} \cdot I_{L_1,ripple} \cdot (t_1 + t_2) \cdot f_{switch}$

Max. Inductor Current: $I_{L_1,max} = I_{L_1,min} + I_{L_1,ripple}$

Average Inductor Current: $I_{L_1,avg} = I_{in,avg}$

Inductor Voltage during t_1: $V_{L_1,t_1} = V_{in}$

Min. Inductor Voltage during t_2: $V_{L_1,min,t_2} = -V_{out} - V_f - \frac{V_{C_1,ripple}}{2}$

Max. Inductor Voltage during t_2: $V_{L_1,max,t_2} = -V_{out} - V_f + \frac{V_{C_1,ripple}}{2}$

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

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.

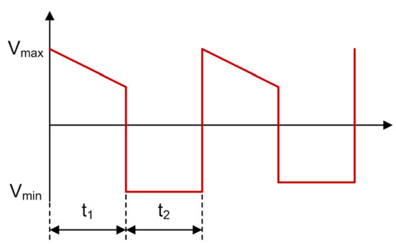


Figure 6.3.1. **SEPIC - Inductor L_2 Voltage Waveform in CCM**

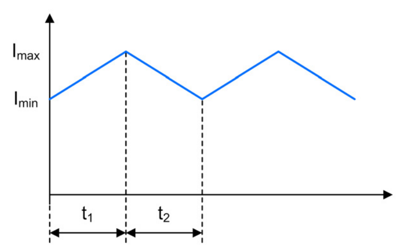


Figure 6.3.2. **SEPIC - Inductor L_2 Current Waveform in CCM**

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.

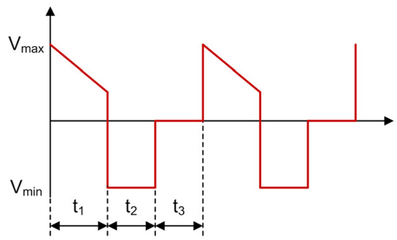


Figure 6.3.3. **SEPIC - Inductor L_2 Voltage Waveform in DCM**

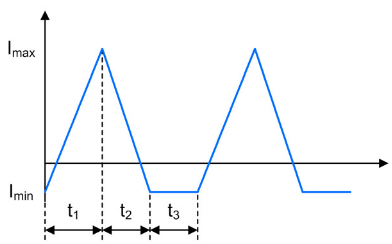


Figure 6.3.4. **SEPIC - Inductor L_2 Current Waveform in DCM**

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

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

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

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.

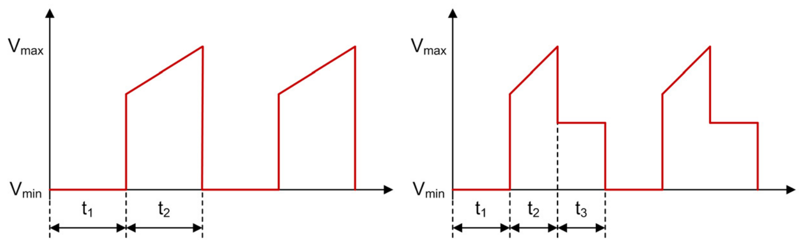


Figure 6.4.1. **SEPIC - FET Q_1 Voltage Waveforms in CCM and DCM**

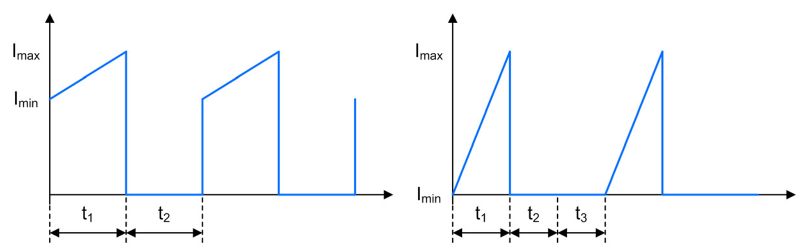


Figure 6.4.2. **SEPIC - FET Q_1 Current Waveforms in CCM and DCM**

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.

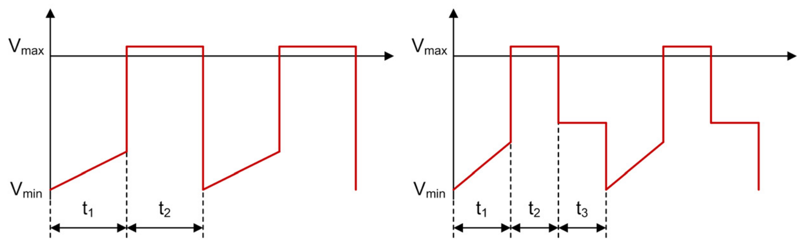


Figure 6.5.1. **SEPIC - Diode D_1 Voltage Waveforms in CCM and DCM**

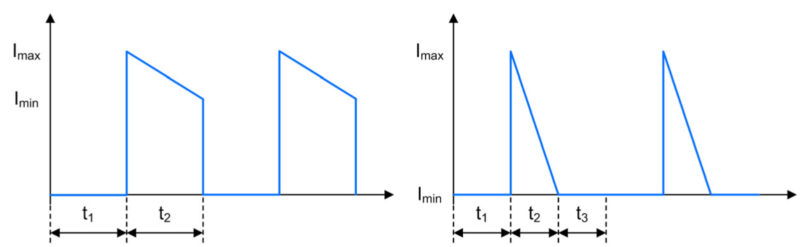


Figure 6.5.2. **SEPIC - Diode D_1 Current Waveforms in CCM and DCM**

Min. Diode Current: $I_{D_1,min} = I_{L_1,min} + I_{L_2,min}$

Max. Diode Current: $I_{D_1,max} = I_{L_1,max} + I_{L_2,max}$

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

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

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

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

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

6.6. Coupling Capacitor C_1

6.6.1. CCM & DCM.

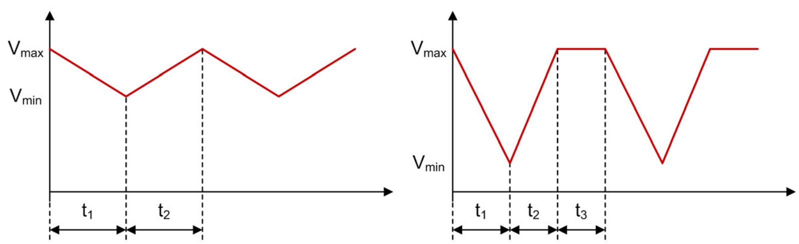


Figure 6.6.1. **SEPIC - Coupling Capacitor C_1 Voltage Waveforms in CCM and DCM**

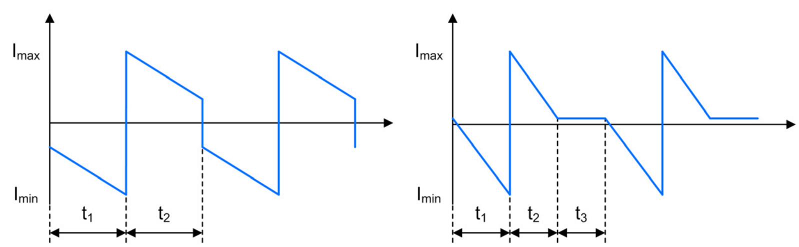


Figure 6.6.2. **SEPIC - Coupling Capacitor C_1 Current Waveforms in CCM and DCM**

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.

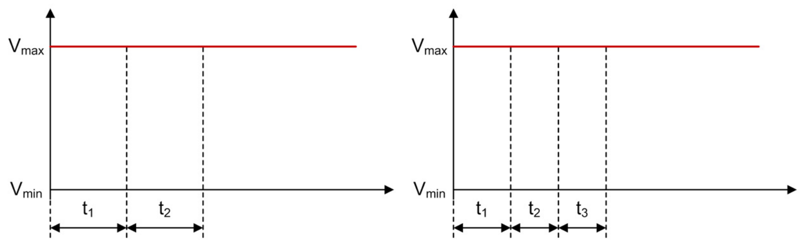


Figure 6.7.1. **SEPIC - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

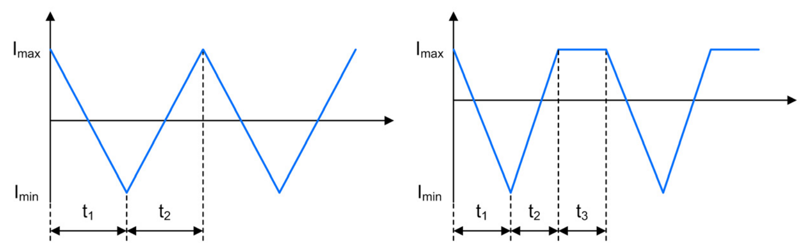


Figure 6.7.2. **SEPIC - Input Capacitor C_i Current Waveforms in CCM and DCM**

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.

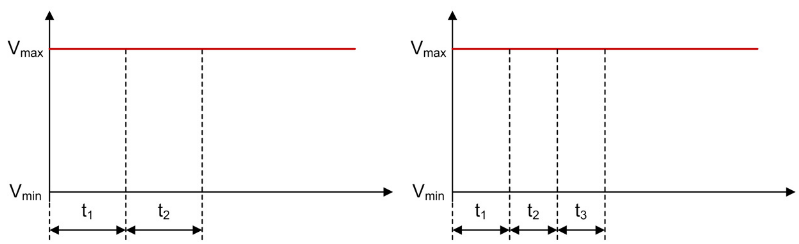


Figure 6.8.1. **SEPIC - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

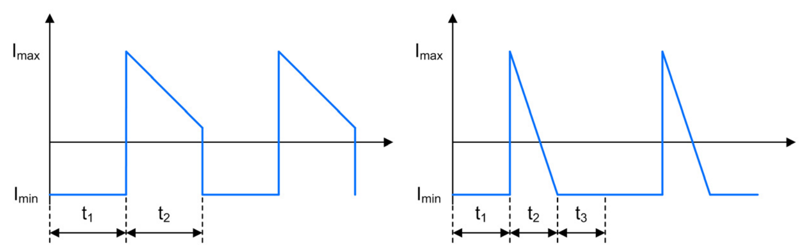


Figure 6.8.2. **SEPIC - Output Capacitor C_o Current Waveforms in CCM and DCM**

Output Capacitor Current during t_1: $I_{C_o,t_1} = -I_{out}$

Min. Output Capacitor Current during t_2 and t_3: $I_{C_o,min,t_{2/3}} = I_{L_1,min} + I_{L_2,min} - I_{out}$

Max. Output Capacitor Current during t_2 and t_3: $I_{C_o,max,t_{2/3}} = I_{L_1,max} + I_{L_2,max} - I_{out}$

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

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

CHAPTER 7

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.

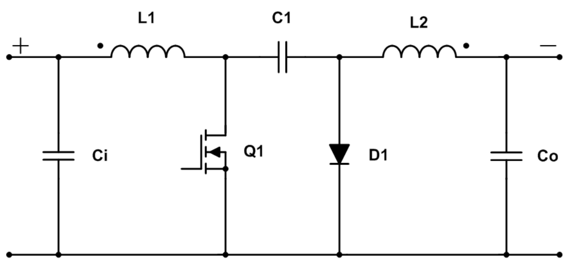


Figure 7.0.1. **Schematic of a Cuk converter**

7.1. General

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

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

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.

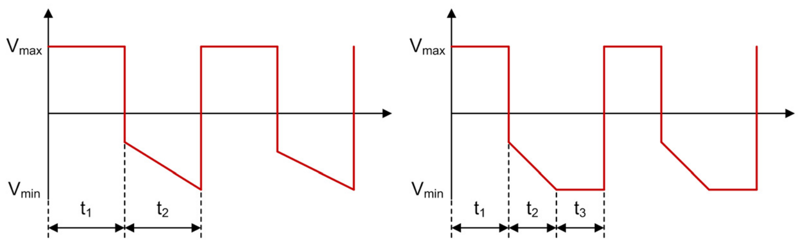


Figure 7.2.1. **Cuk - Inductor L_1 Voltage Waveforms in CCM and DCM**

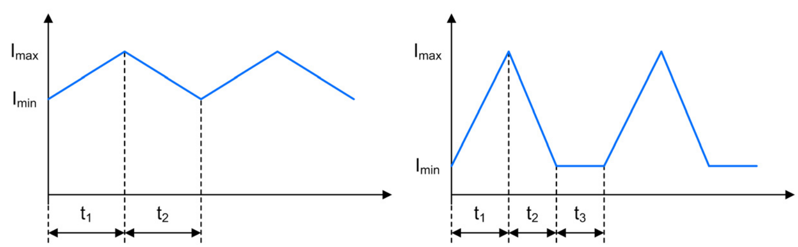


Figure 7.2.2. **Cuk - Inductor L_1 Current Waveforms in CCM and DCM**

Min. Inductor Current: $I_{L_1,min} = I_{in,avg} - \frac{1}{2} \cdot I_{L_1,ripple} \cdot (t_1 + t_2) \cdot f_{switch}$

Max. Inductor Current: $I_{L_1,max} = I_{L_1,min} + I_{L_1,ripple}$

Average Inductor Current: $I_{L_1,avg} = I_{in,avg}$

Inductor Voltage during t_1: $V_{L_1,t_1} = V_{in}$

Min. Inductor Voltage during t_2: $V_{L_1,min,t_2} = V_{out} - V_f - \frac{V_{C_1,ripple}}{2}$

Max. Inductor Voltage during t_2: $V_{L_1,max,t_2} = V_{out} - V_f + \frac{V_{C_1,ripple}}{2}$

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

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.

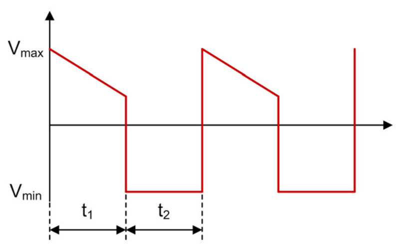


Figure 7.3.1. **Cuk - Inductor L_2 Voltage Waveform in CCM**

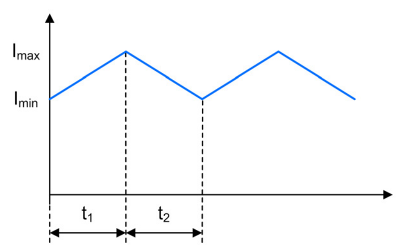


Figure 7.3.2. **Cuk - Inductor L_2 Current Waveform in CCM**

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.

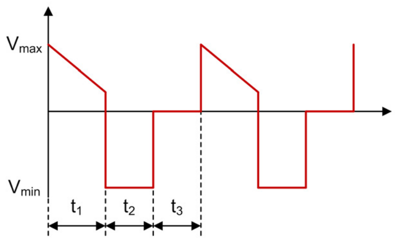


Figure 7.3.3. **Cuk - Inductor L_2 Voltage Waveform in DCM**

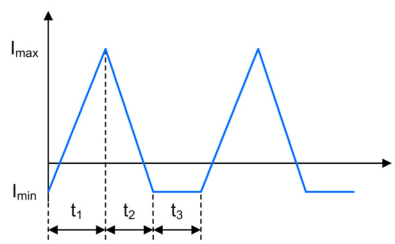


Figure 7.3.4. **Cuk - Inductor L_2 Current Waveform in DCM**

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

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

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

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.

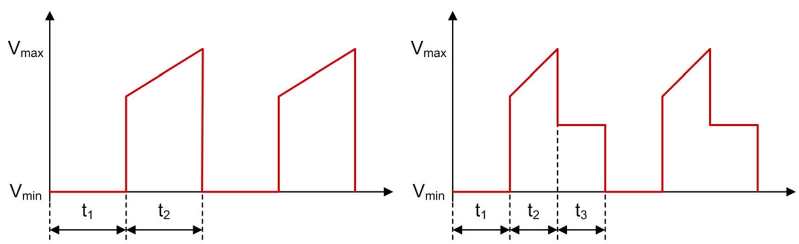


Figure 7.4.1. **Cuk - FET Q_1 Voltage Waveforms in CCM and DCM**

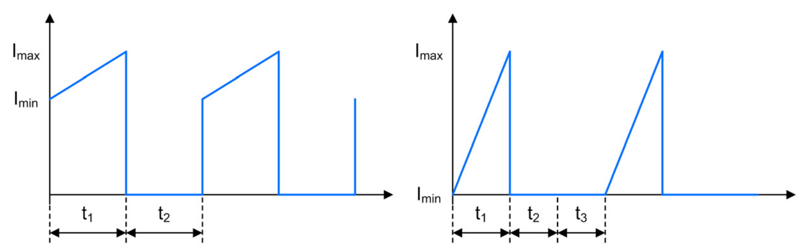


Figure 7.4.2. **Cuk - FET Q_1 Current Waveforms in CCM and DCM**

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.

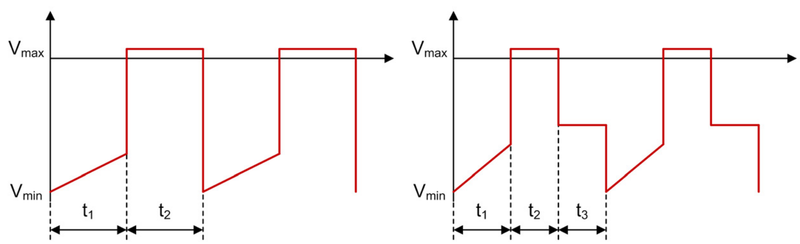


Figure 7.5.1. **Cuk - Diode D_1 Voltage Waveforms in CCM and DCM**

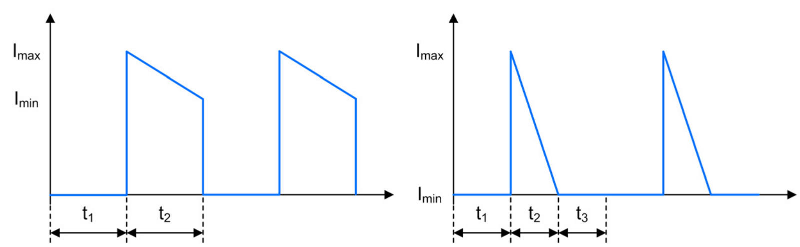


Figure 7.5.2. **Cuk - Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

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

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

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

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

7.6. Coupling Capacitor C_1

7.6.1. CCM & DCM.

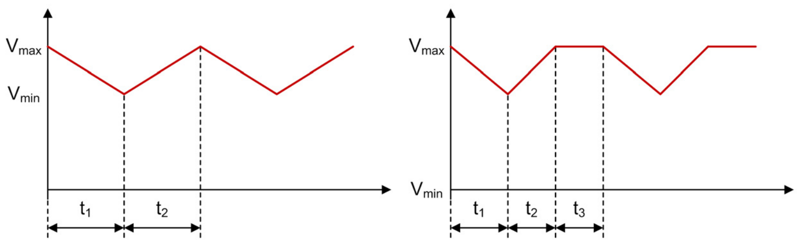


Figure 7.6.1. **Cuk - Coupling Capacitor C_1 Voltage Waveforms in CCM and DCM**

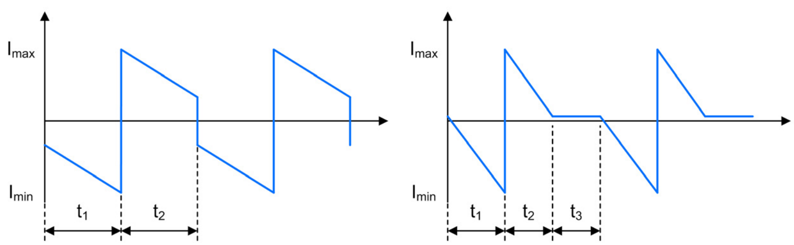


Figure 7.6.2. **Cuk - Coupling Capacitor C_1 Current Waveforms in CCM and DCM**

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.

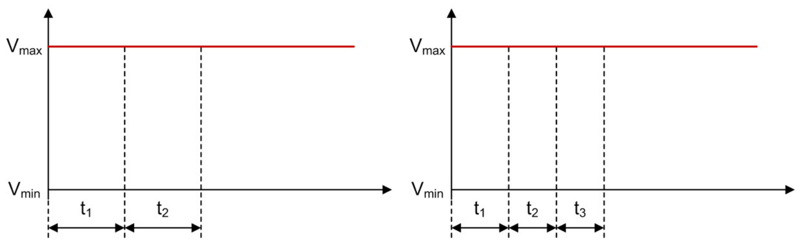


Figure 7.7.1. **Cuk - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

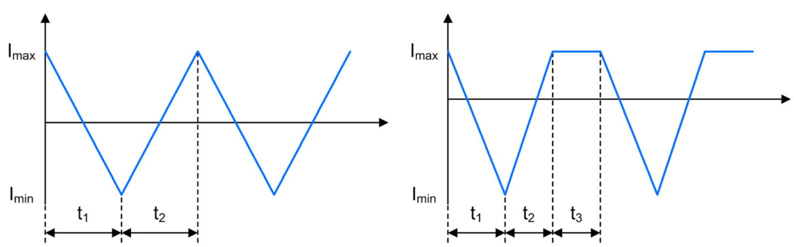


Figure 7.7.2. **Cuk - Input Capacitor C_i Current Waveforms in CCM and DCM**

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: $V_{C_i} = V_{in}$

7.8. Output Capacitor C_o

7.8.1. CCM & DCM.

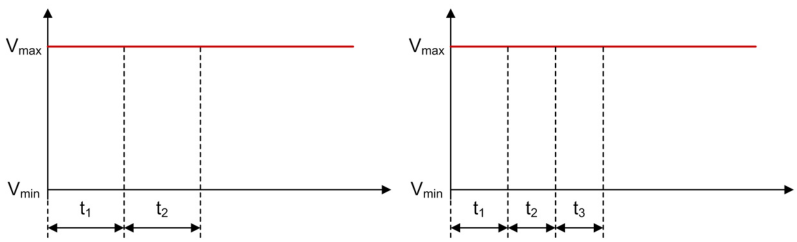


Figure 7.8.1. **Cuk - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

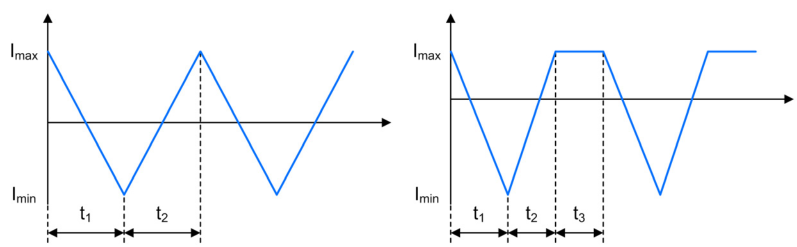


Figure 7.8.2. **Cuk - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

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

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

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

CHAPTER 8

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.

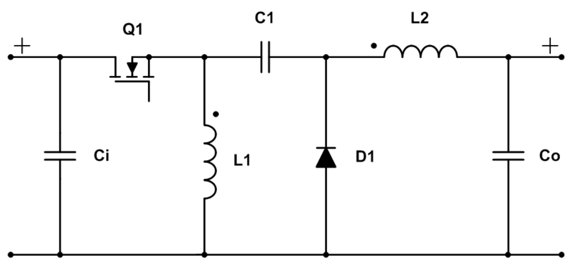


Figure 8.0.1. **Schematic of a Zeta converter**

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

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

Coupling Capacitor C_1 Voltage Ripple: $V_{C_1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$

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

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

Coupling Capacitor C_1 Voltage Ripple: $V_{C_1,ripple} = I_{in,avg} \cdot \frac{1-D}{C_1 \cdot f_{switch}}$

8.2. Inductor L_1

8.2.1. CCM & DCM.

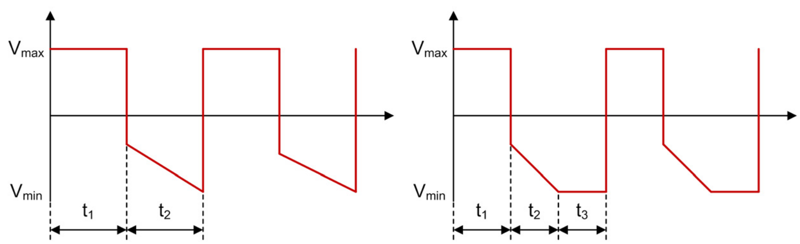


Figure 8.2.1. **Zeta - Inductor L_1 Voltage Waveforms in CCM and DCM**

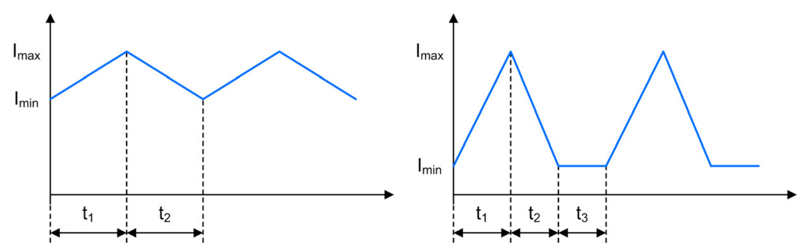


Figure 8.2.2. **Zeta - Inductor L_1 Current Waveforms in CCM and DCM**

Min. Inductor Current: $I_{L_1,min} = I_{in,avg} - \frac{1}{2} \cdot I_{L_1,ripple} \cdot (t_1 + t_2) \cdot f_{switch}$

Max. Inductor Current: $I_{L_1,max} = I_{L_1,min} + I_{L_1,ripple}$

Average Inductor Current: $I_{L_1,avg} = I_{in,avg}$

Inductor Voltage during t_1: $V_{L_1,on} = V_{in}$

Min. Inductor Voltage during t_2: $V_{L_1,min,t_2} = -V_{out} - V_f - \frac{V_{C_1,ripple}}{2}$

Max. Inductor Voltage during t_2: $V_{L_1,max,t_2} = -V_{out} - V_f + \frac{V_{C_1,ripple}}{2}$

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

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

8.3. Inductor L_2

8.3.1. CCM.

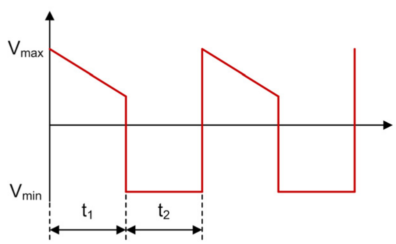


Figure 8.3.1. **Zeta - Inductor L_2 Voltage Waveform in CCM**

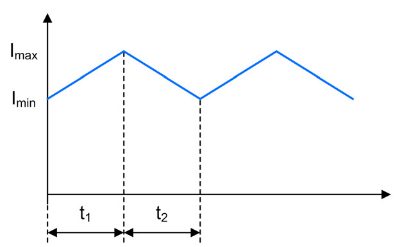


Figure 8.3.2. **Zeta - Inductor L_2 Current Waveform in CCM**

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

8.3.2. DCM.

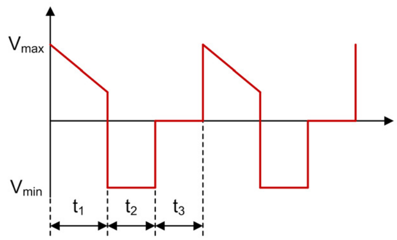


Figure 8.3.3. **Zeta - Inductor L_2 Voltage Waveform in DCM**

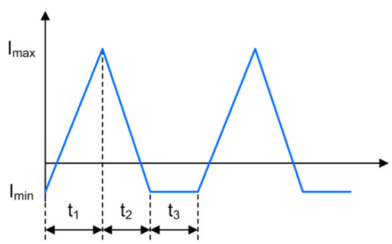


Figure 8.3.4. **Zeta - Inductor L_2 Current Waveform in DCM**

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

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

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

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.

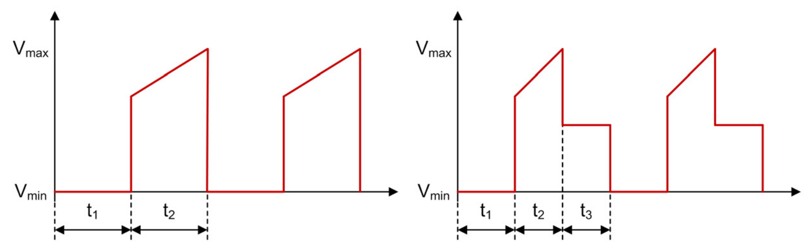


Figure 8.4.1. **Zeta - FET Q_1 Voltage Waveforms in CCM and DCM**

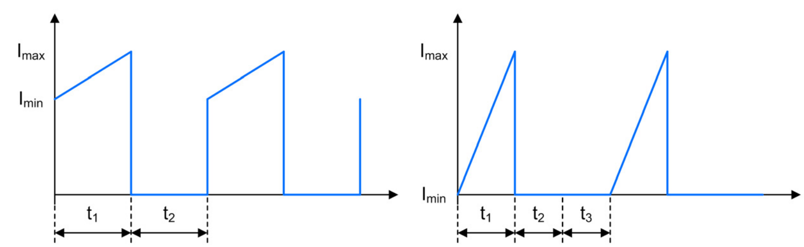


Figure 8.4.2. **Zeta - FET Q_1 Current Waveforms in CCM and DCM**

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

8.5. Diode D_1

8.5.1. CCM & DCM.

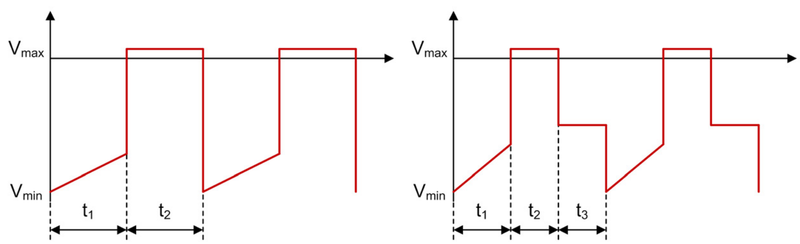


Figure 8.5.1. **Zeta - Diode D_1 Voltage Waveforms in CCM and DCM**

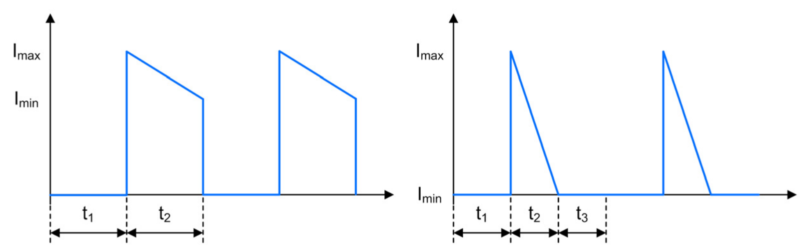


Figure 8.5.2. **Zeta - Diode D_1 Current Waveforms in CCM and DCM**

Min. Diode Current: $I_{D_1,min} = I_{L_1,min} + I_{L_2,min}$

Max. Diode Current: $I_{D_1,max} = I_{L_1,max} + I_{L_2,max}$

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

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

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

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

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

8.6. Coupling Capacitor C_1

8.6.1. CCM & DCM.

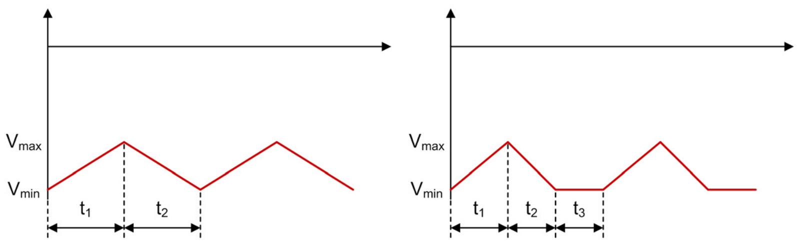


Figure 8.6.1. **Zeta - Coupling Capacitor C_1 Voltage Waveforms in CCM and DCM**

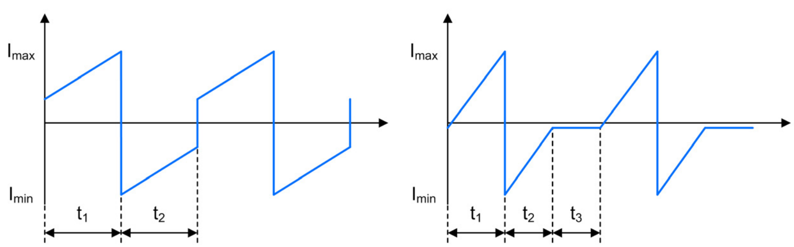


Figure 8.6.2. **Zeta - Coupling Capacitor C_1 Current Waveforms in CCM and DCM**

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.

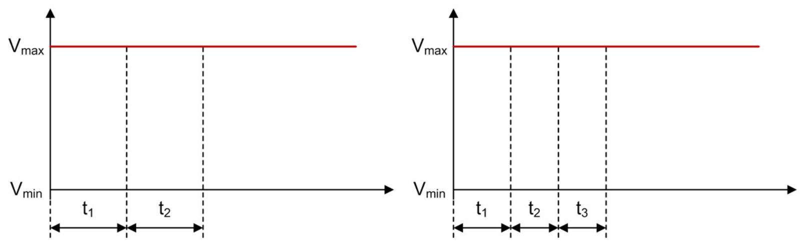


Figure 8.7.1. **Zeta - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

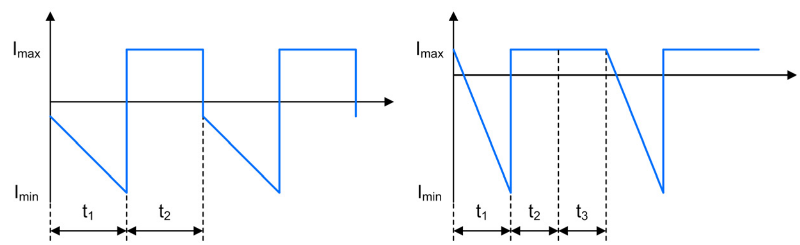


Figure 8.7.2. **Zeta - Input Capacitor C_i Current Waveforms in CCM and DCM**

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.

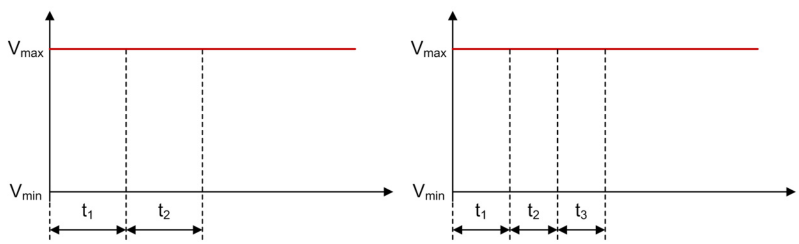


Figure 8.8.1. **Zeta - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

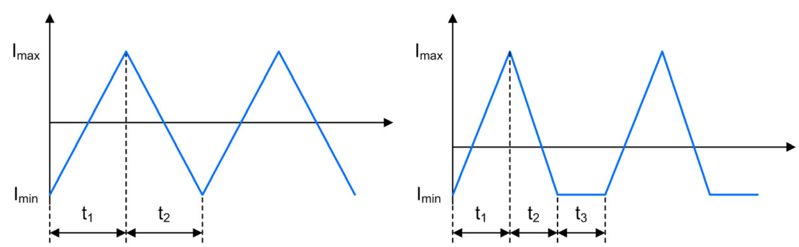


Figure 8.8.2. **Zeta - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

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

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

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

CHAPTER 9

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.

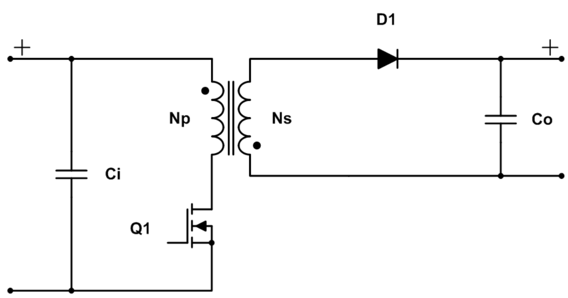


Figure 9.0.1. **Schematic of a Flyback converter**

9.1. General

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

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

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.

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

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

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

9.1.3. Transition Mode.

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

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.

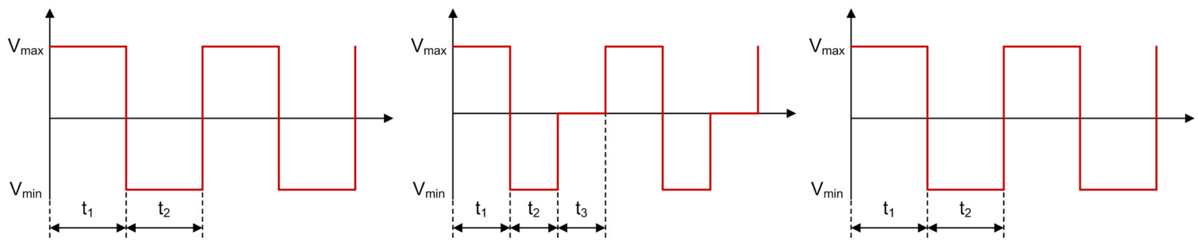


Figure 9.2.1. **Flyback - Primary Side Inductor N_p Voltage Waveforms in CCM, DCM and Transition Mode**

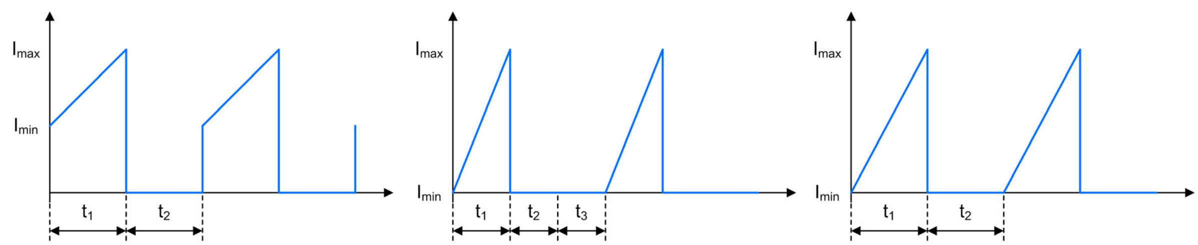


Figure 9.2.2. **Flyback - Primary Side Inductor N_p Current Waveforms in CCM, DCM and Transition Mode**

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

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

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

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

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

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

9.3. Secondary Side Inductor N_s

9.3.1. CCM.

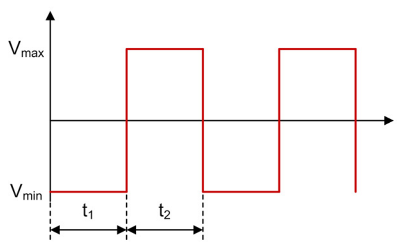


Figure 9.3.1. **Flyback - Secondary Side Inductor N_s Voltage Waveform in CCM**

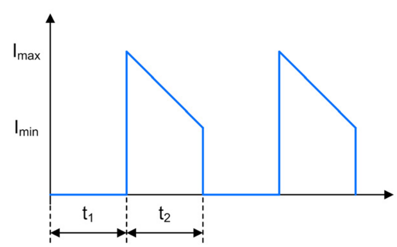


Figure 9.3.2. **Flyback - Secondary Side Inductor N_s Current Waveform in CCM**

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.

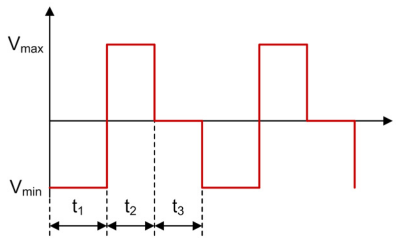


Figure 9.3.3. **Flyback - Secondary Side Inductor N_s Voltage Waveform in DCM**

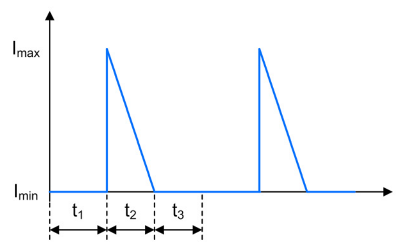


Figure 9.3.4. **Flyback - Secondary Side Inductor N_s Current Waveform in DCM**

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.

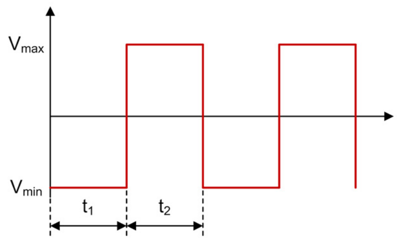


Figure 9.3.5. **Flyback - Secondary Side Inductor N_s Voltage Waveform in Transition Mode**

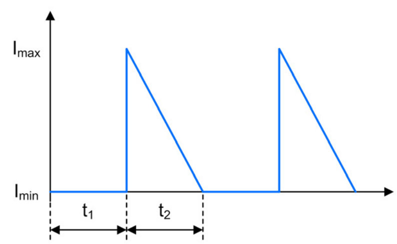


Figure 9.3.6. **Flyback - Secondary Side Inductor N_s Current Waveform in Transition Mode**

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.

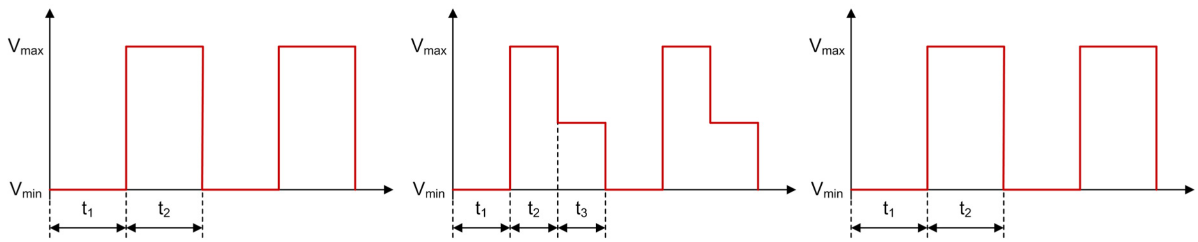


Figure 9.4.1. **Flyback - FET Q_1 Voltage Waveforms in CCM, DCM and Transition Mode**

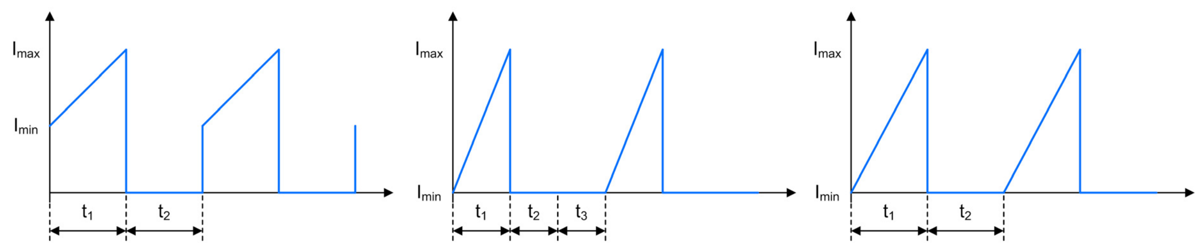


Figure 9.4.2. **Flyback - FET Q_1 Current Waveforms in CCM, DCM and Transition Mode**

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.

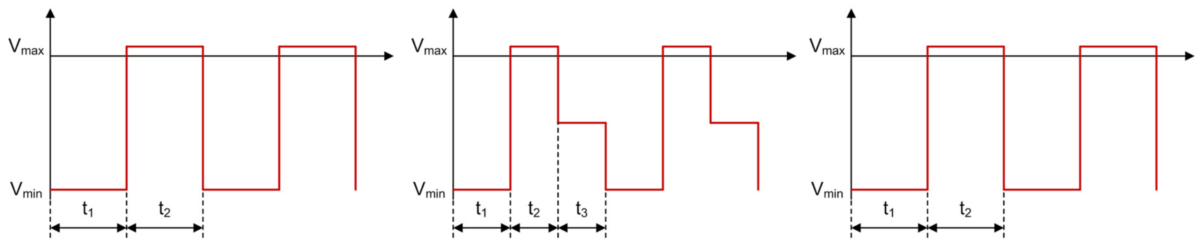


Figure 9.5.1. **Flyback - Diode D_1 Voltage Waveforms in CCM, DCM and Transition Mode**

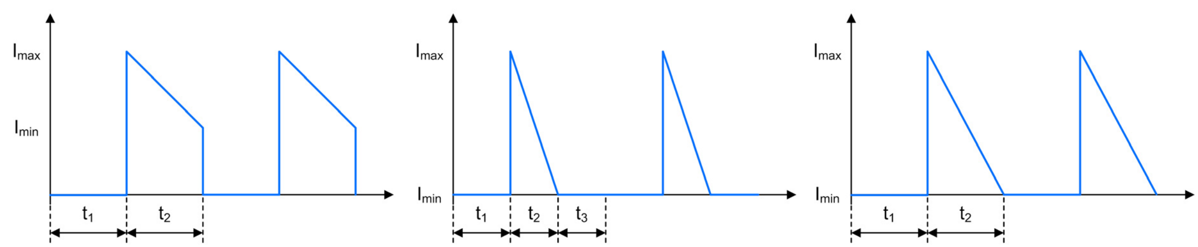


Figure 9.5.2. **Flyback - Diode D_1 Current Waveforms in CCM, DCM and Transition Mode**

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

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

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

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

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

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

9.6. Input Capacitor C_i

9.6.1. CCM.

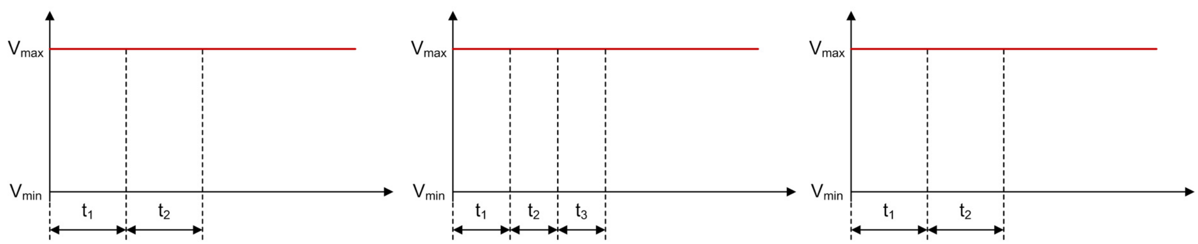


Figure 9.6.1. **Flyback - Input Capacitor C_i Voltage Waveforms in CCM, DCM and Transition Mode**

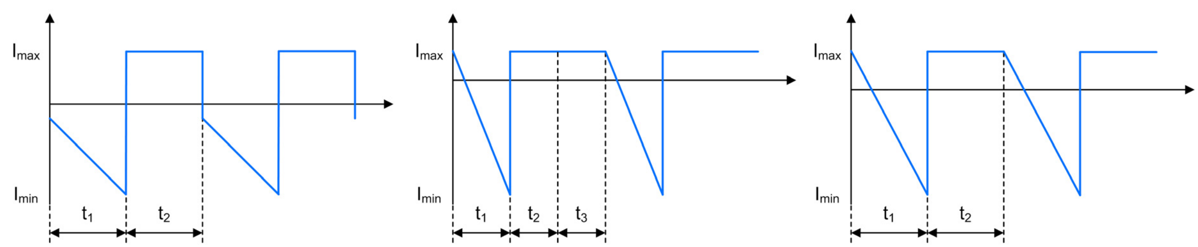


Figure 9.6.2. **Flyback - Input Capacitor C_i Current Waveforms in CCM, DCM and Transition Mode**

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.

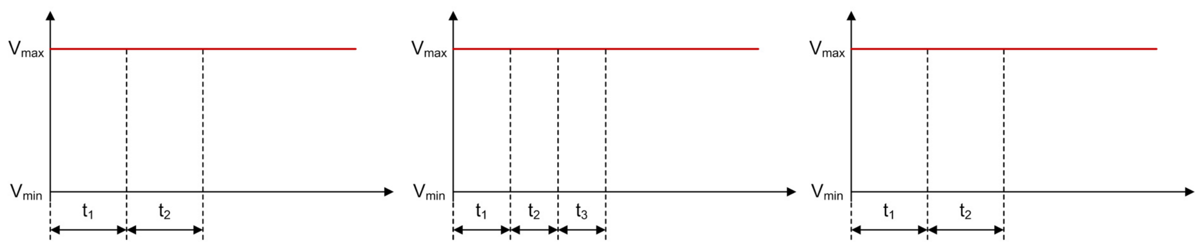


Figure 9.7.1. **Flyback - Output Capacitor C_o Voltage Waveforms in CCM, DCM and Transition Mode**

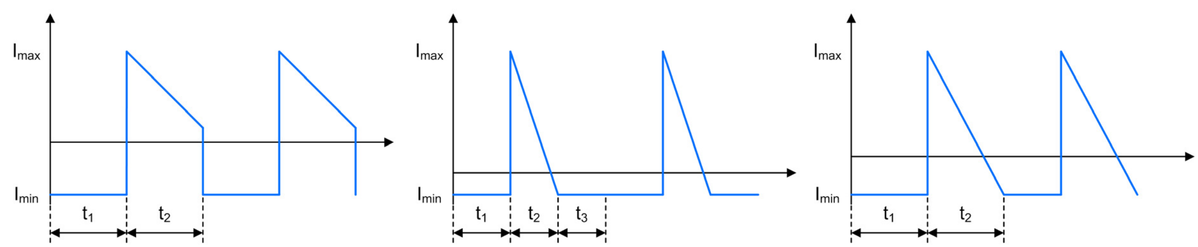


Figure 9.7.2. **Flyback - Output Capacitor C_o Current Waveforms in CCM, DCM and Transition Mode**

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

CHAPTER 10

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.

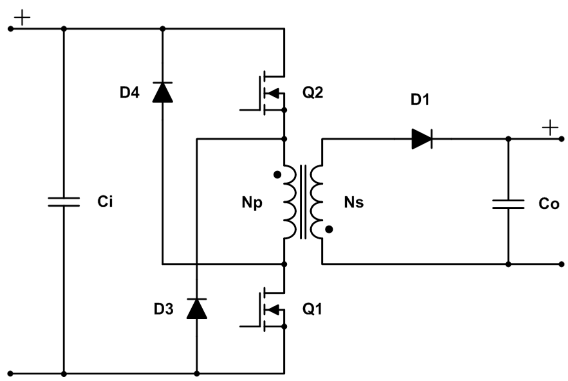


Figure 10.0.1. **Schematic of a Two Switch Flyback converter**

10.1. General

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

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

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: $t_1 = \frac{1}{f_{switch}} \cdot (V_{out} + V_f) \cdot \frac{\frac{p^n}{n_s}}{V_{in} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}}$

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.

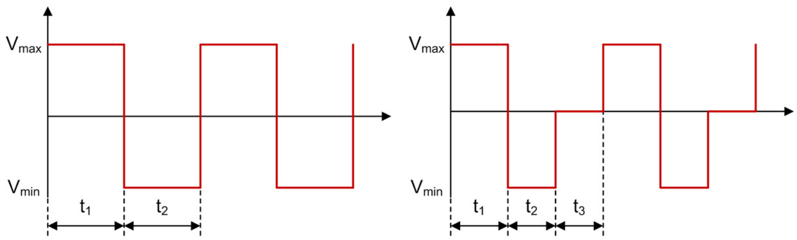


Figure 10.2.1. **Two Switch Flyback - Primary Side Inductor N_p Voltage Waveforms in CCM and DCM**

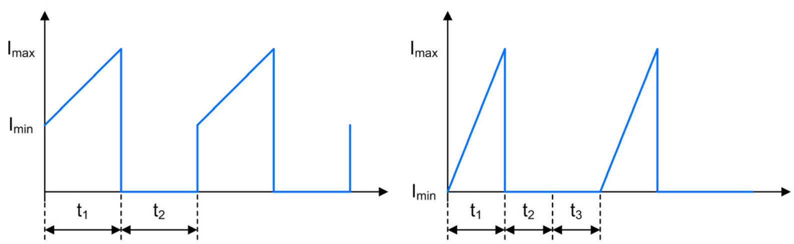


Figure 10.2.2. **Two Switch Flyback - Primary Side Inductor N_p Current Waveforms in CCM and DCM**

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

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

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

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

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

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

10.3. Secondary Side Inductor N_s

10.3.1. CCM & DCM.

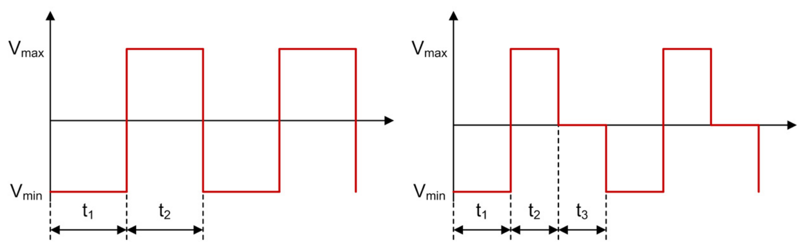


Figure 10.3.1. **Two Switch Flyback - Secondary Side Inductor N_s VoltageWaveforms in CCM and DCM**

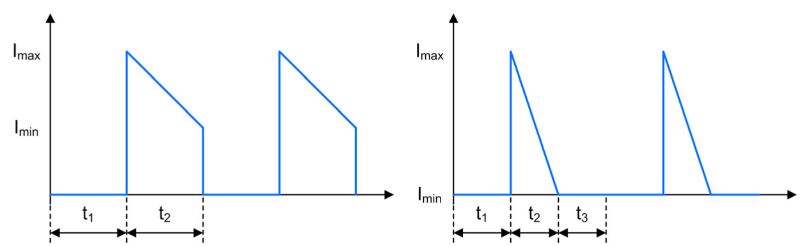


Figure 10.3.2. **Two Switch Flyback - Secondary Side Inductor N_s Current Waveforms in CCM and DCM**

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

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: $V_{N_s,t_3} = 0V$

10.4. FET Q_1 / Q_2

10.4.1. CCM & DCM.

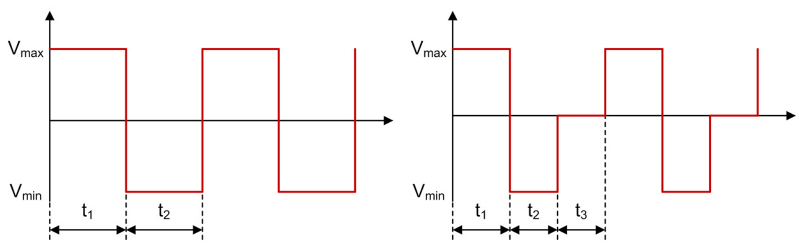


Figure 10.4.1. **Two Switch Flyback - FET Q_1 / Q_2 Voltage Waveforms in CCM and DCM**

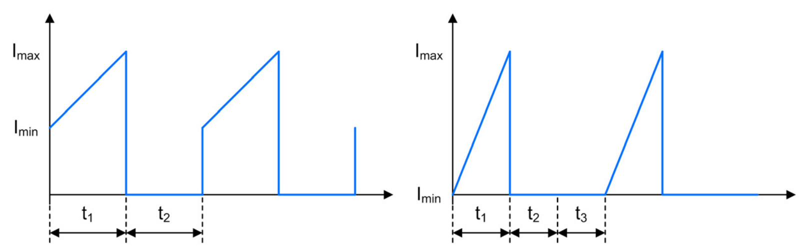


Figure 10.4.2. **Two Switch Flyback - FET Q_1 / Q_2 Current Waveforms in CCM and DCM**

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: $V_{Q_{1/2},t_3} = \frac{V_{in}}{2}$

10.5. Diode D_1

10.5.1. CCM & DCM.

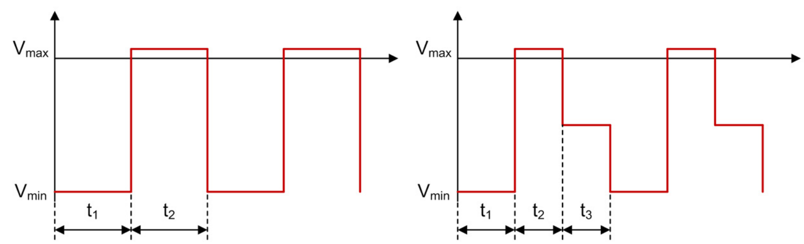


Figure 10.5.1. **Two Switch Flyback - Diode D_1 VoltageWaveforms in CCM and DCM**

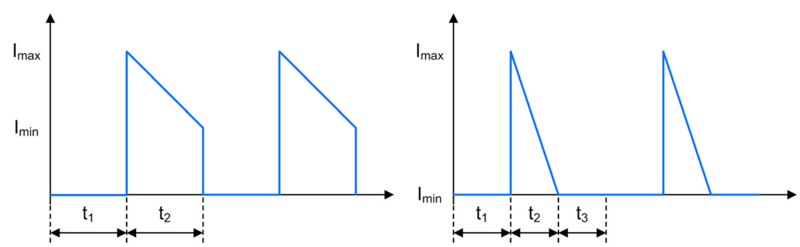


Figure 10.5.2. **Two Switch Flyback - Diode D_1 Current Waveforms in CCM and DCM**

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.

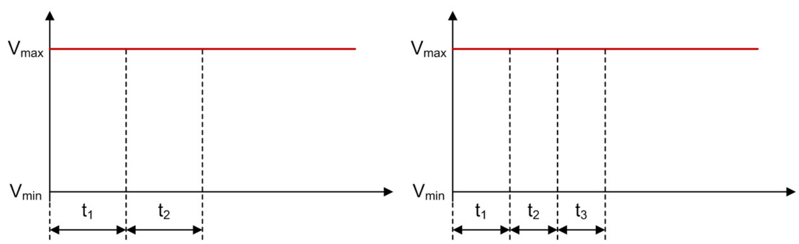


Figure 10.6.1. **Two Switch Flyback - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

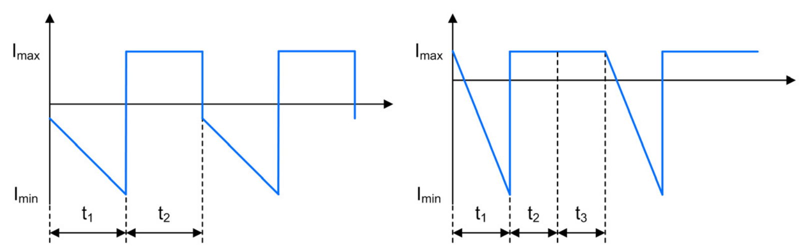


Figure 10.6.2. **Two Switch Flyback - Input Capacitor C_i Current Waveforms in CCM and DCM**

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: $V_{C_i} = V_{in}$

10.7. Output Capacitor C_o

10.7.1. CCM & DCM.

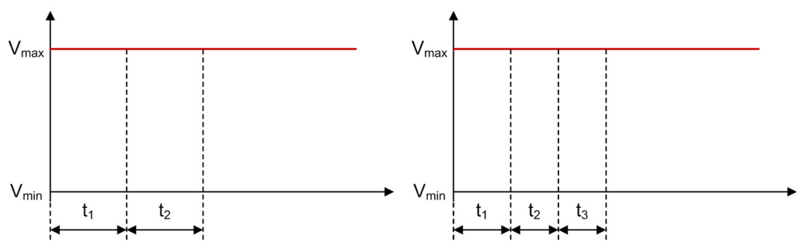


Figure 10.7.1. **Two Switch Flyback - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

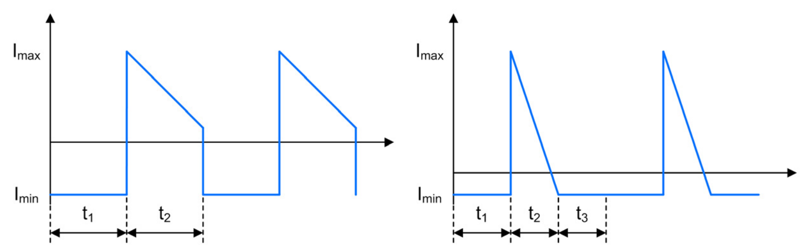


Figure 10.7.2. **Two Switch Flyback - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

CHAPTER 11

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.

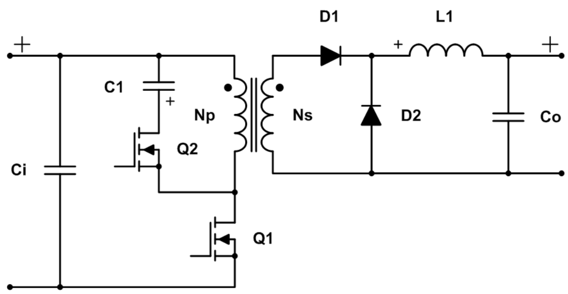


Figure 11.0.1. **Schematic of an Active Clamp Forward converter**

11.1. General

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

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: $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot \left(V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}\right) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

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.

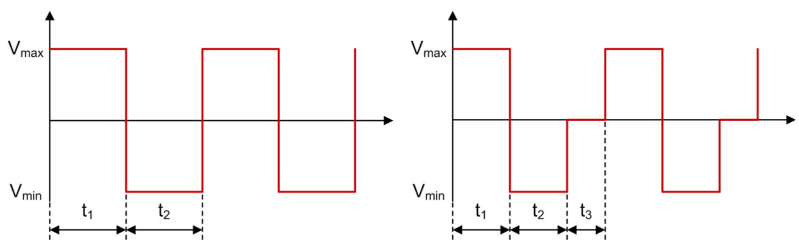


Figure 11.2.1. **Active Clamp Forward - Primary Side Transformer Winding Voltage N_p Waveforms in CCM and DCM**

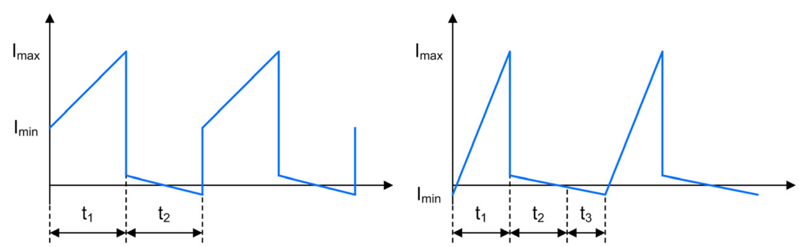


Figure 11.2.2. **Active Clamp Forward - Primary Side Transformer Winding N_p Current Waveforms in CCM and DCM**

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 at the start of t_3: $V_{N_p,t_3} = 0V$

11.3. Secondary Side Transformer Winding N_s

11.3.1. CCM & DCM.

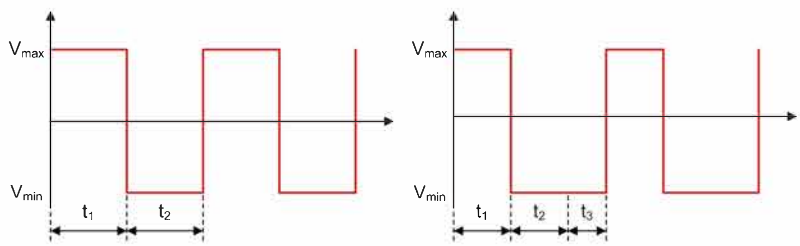


Figure 11.3.1. **Active Clamp Forward - Secondary Side Transformer Winding N_s Voltage Waveforms in CCM and DCM**

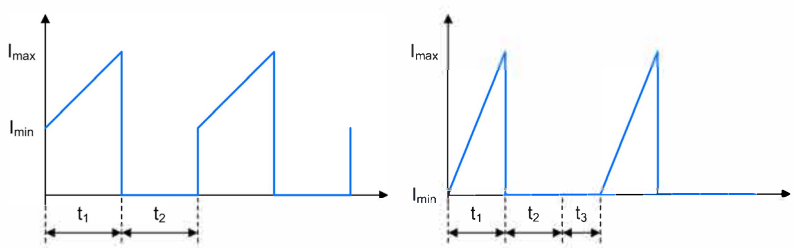


Figure 11.3.2. **Active Clamp Forward - Secondary Side Transformer Winding N_s Current Waveforms in CCM and DCM**

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: $V_{N_s,t_1} = V_{in} \cdot \frac{n_s}{n_p}$

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

11.4. Inductor L_1

11.4.1. CCM & DCM.

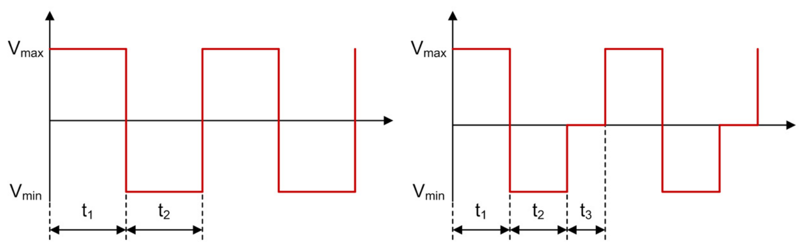


Figure 11.4.1. **Active Clamp Forward - Inductor L_1 Voltage Waveforms in CCM and DCM**

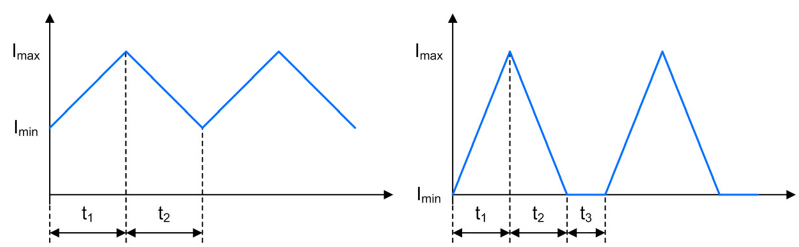


Figure 11.4.2. **Active Clamp Forward - Inductor L_1 Current Waveforms in CCM and DCM**

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.

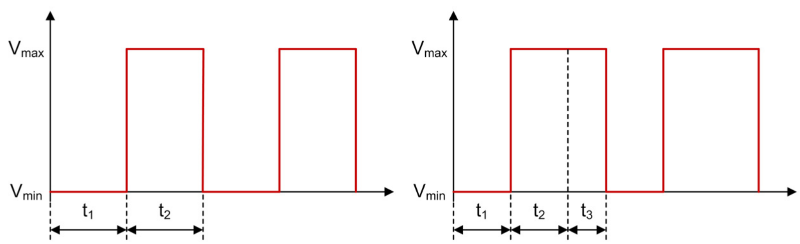


Figure 11.5.1. **Active Clamp Forward - FET Q_1 Voltage Waveforms in CCM and DCM**

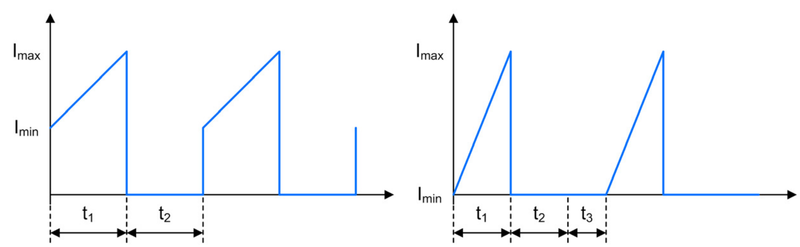


Figure 11.5.2. **Active Clamp Forward - FET Q_1 Current Waveforms in CCM and DCM**

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: $V_{Q_1,t_3} = \frac{V_{in}}{1 - D}$

11.6. Clamping FET Q_2

11.6.1. CCM & DCM.

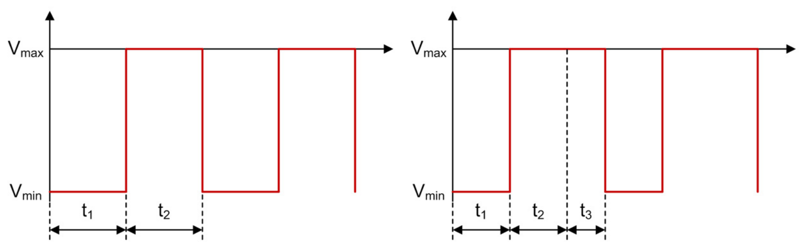


Figure 11.6.1. **Active Clamp Forward - Clamping FET Q_2 Voltage Waveforms in CCM and DCM**

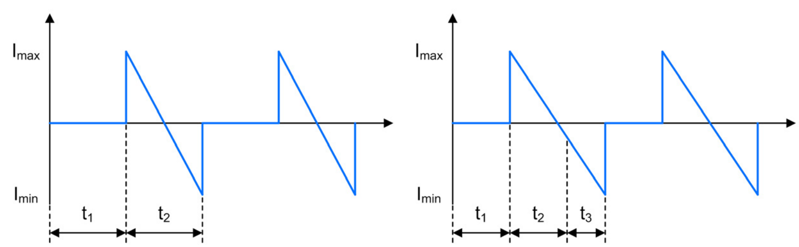


Figure 11.6.2. **Active Clamp Forward - Clamping FET Q_2 Current Waveforms in CCM and DCM**

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 Curren 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 FETVoltage during t_3:	$V_{Q_2,t_3} = 0V$

11.7. Clamping Capacitor C_1

11.7.1. CCM & DCM.

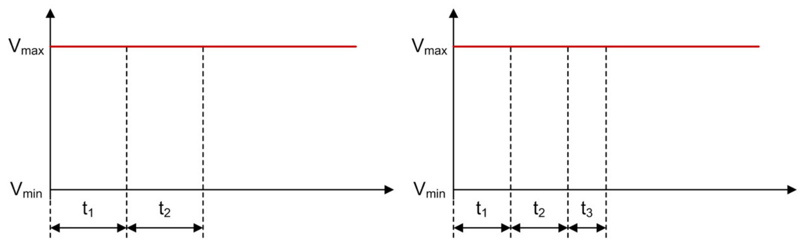


Figure 11.7.1. **Active Clamp Forward - Clamping Capacitor C_1 Voltage Waveforms in CCM and DCM**

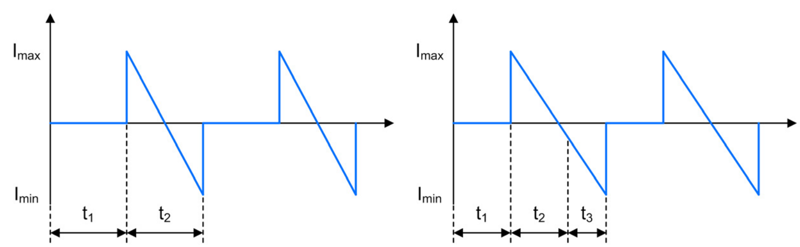


Figure 11.7.2. **Active Clamp Forward - Clamping Capacitor C_1 Current Waveforms in CCM and DCM**

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 Curren 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.

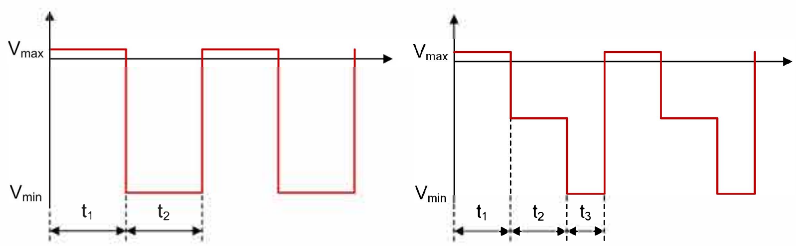


Figure 11.8.1. **Active Clamp Forward - Rectifier Diode D_1 Voltage Waveforms in CCM and DCM**

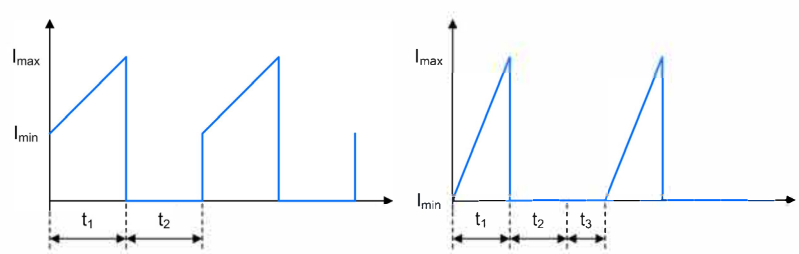


Figure 11.8.2. **Active Clamp Forward - Rectifier Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

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

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

Rectifier Diode Voltage during t_3: $V_{D_1,t_3} = -V_{clamp} \cdot \frac{n_s}{n_p} - V_{out}$

11.9. Freewheeling Diode D_2

11.9.1. CCM & DCM.

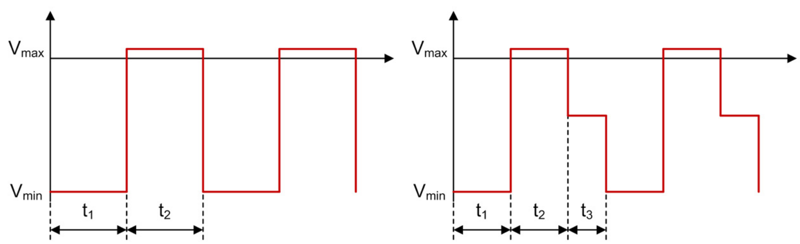


Figure 11.9.1. **Active Clamp Forward - Freewheeling Diode D_2 Voltage Waveforms in CCM and DCM**

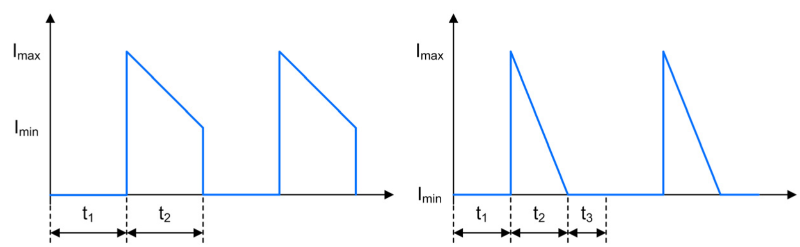


Figure 11.9.2. **Active Clamp Forward - Freewheeling Diode D_2 Current Waveforms in CCM and DCM**

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: $V_{D_2,t_3} = -V_{out}$

11.10. Input Capacitor C_i

11.10.1. CCM & DCM.

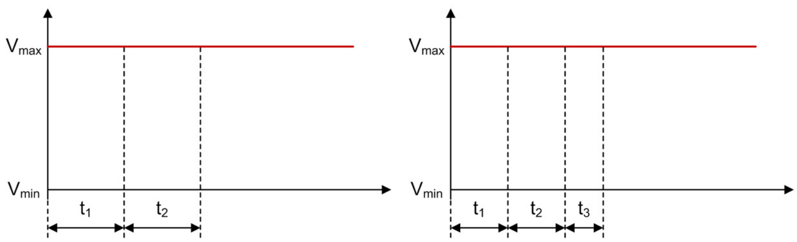


Figure 11.10.1. **Active Clamp Forward - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

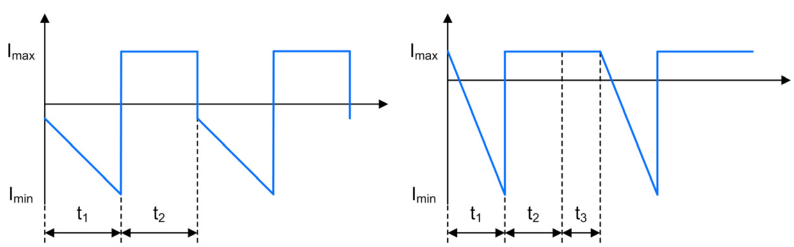


Figure 11.10.2. **Active Clamp Forward - Input Capacitor C_i Current Waveforms in CCM and DCM**

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

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

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: $V_{C_i} = V_{in}$

11.11. Output Capacitor C_o

11.11.1. CCM & DCM.

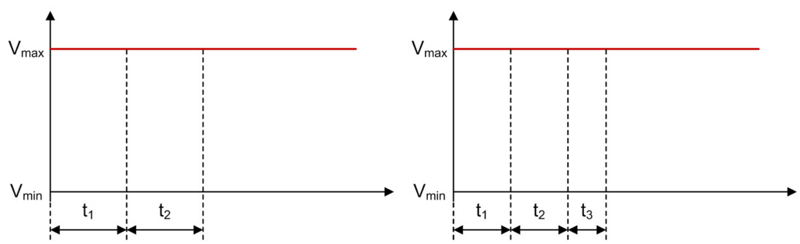


Figure 11.11.1. **Active Clamp Forward - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

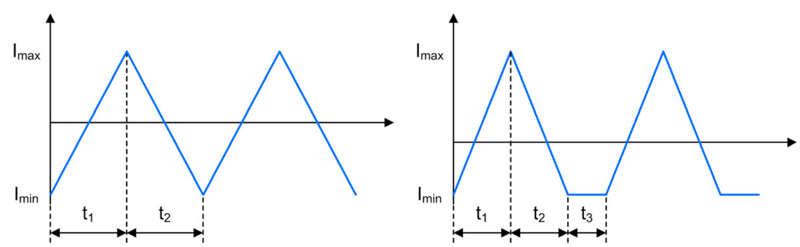


Figure 11.11.2. **Active Clamp Forward - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

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

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

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

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

CHAPTER 12

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.

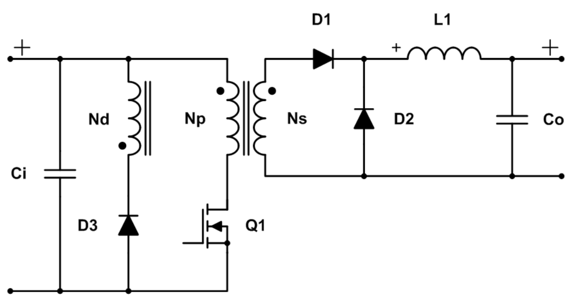


Figure 12.0.1. **Schematic of a Single Switch Forward converter**

12.1. General

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

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: $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot \left(V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}\right) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

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.

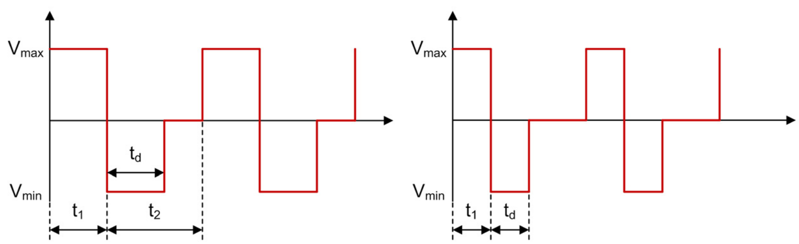


Figure 12.2.1. **Single Switch Forward - Primary Side Transformer Winding N_p Voltage Waveforms in CCM and DCM**

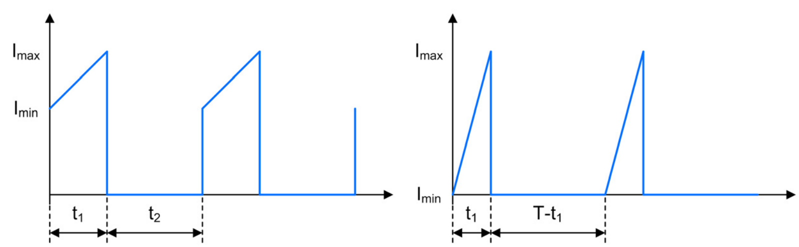


Figure 12.2.2. **Single Switch Forward - Primary Side Transformer Winding N_p Current Waveforms in CCM and DCM**

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

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.

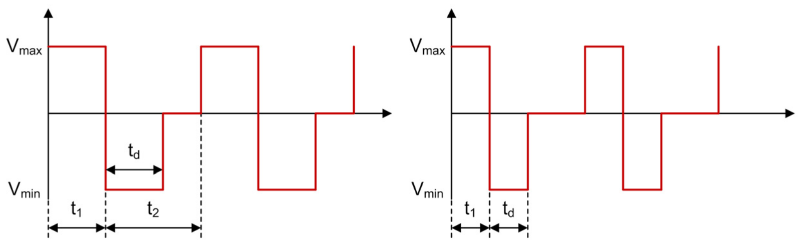


Figure 12.3.1. **Single Switch Forward - Secondary Side Transformer Winding N_s Voltage Waveforms in CCM and DCM**

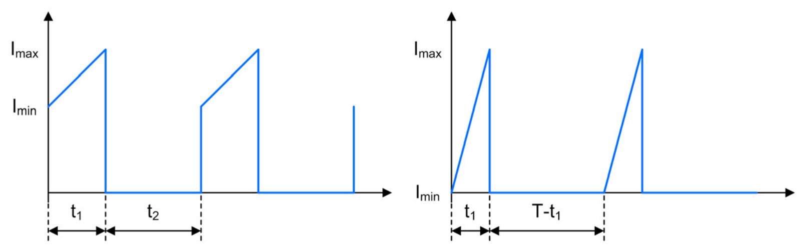


Figure 12.3.2. **Single Switch Forward - Secondary Side Transformer Winding N_s Current Waveforms in CCM and DCM**

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: $V_{N_s,min} = -(V_{in} + V_f) \cdot \frac{n_s}{n_p}$

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: $V_{N_s,t_3} = 0V$

12.4. Inductor L_1

12.4.1. CCM & DCM.

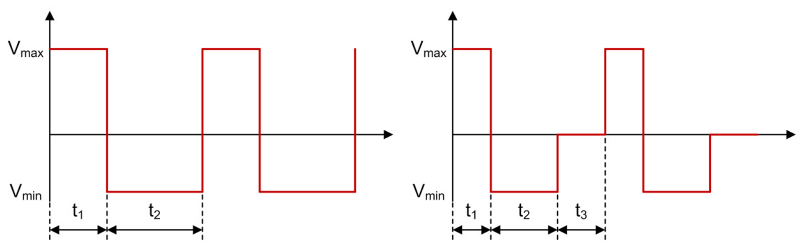


Figure 12.4.1. **Single Switch Forward - Inductor L_1 Voltage Waveforms in CCM and DCM**

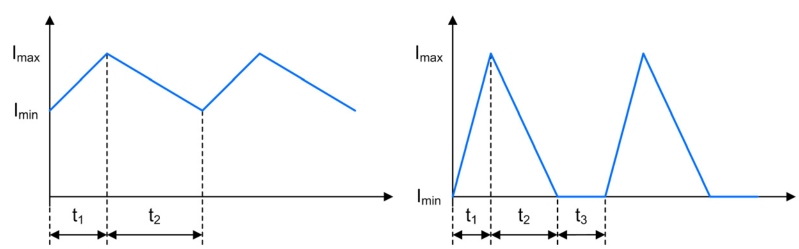


Figure 12.4.2. **Single Switch Forward - Inductor L_1 Current Waveforms in CCM and DCM**

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.

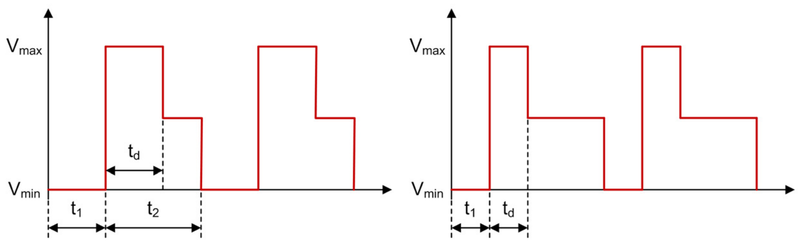


Figure 12.5.1. **Single Switch Forward - FET Q_1 Voltage Waveforms in CCM and DCM**

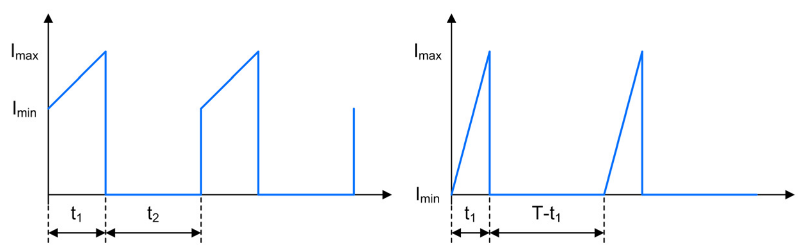


Figure 12.5.2. **Single Switch Forward - FET Q_1 Current Waveforms in CCM and DCM**

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: $V_{Q_1,max} = 2 \cdot V_{in} + Vf$

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.

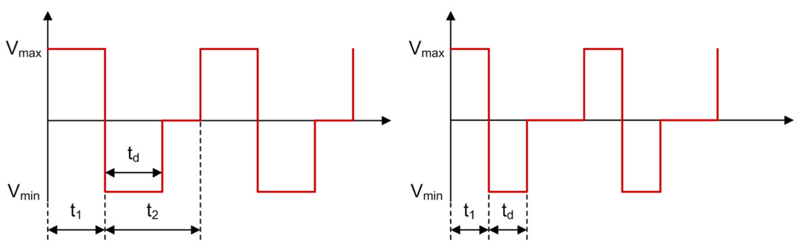


Figure 12.6.1. **Single Switch Forward - Demagnetization Winding N_d Voltage Waveforms in CCM and DCM**

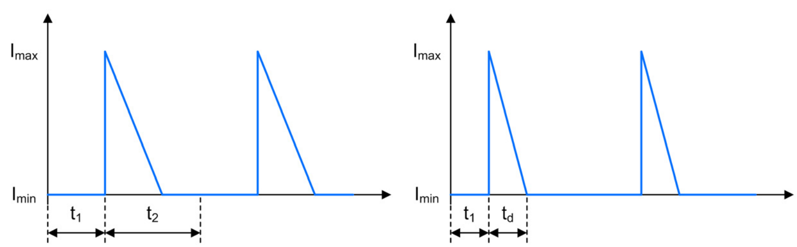


Figure 12.6.2. **Single Switch Forward - Demagnetization Winding N_d Current Waveforms in CCM and DCM**

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

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

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

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

Max. Demagnetization Winding Voltage: $V_{N_d,max} = V_{in}$

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

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

12.7. Demagnetization Diode D_3

12.7.1. CCM & DCM.

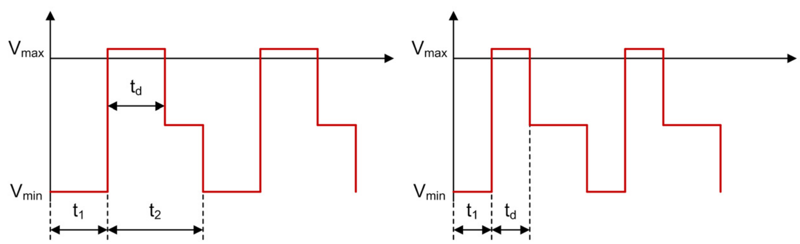


Figure 12.7.1. **Single Switch Forward - Demagnetization Diode D_3 Voltage Waveforms in CCM and DCM**

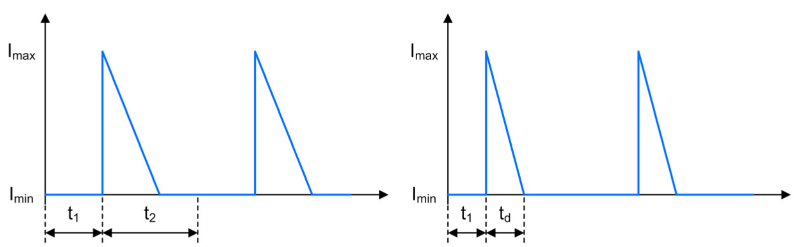


Figure 12.7.2. **Single Switch Forward - Demagnetization Diode D_3 Current Waveforms in CCM and DCM**

Average Demagnetization Diode Current: $I_{D_3,avg} = \frac{I_{mag}}{2} \cdot t_d \cdot f_{switch}$

Min. Demagnetization Diode Current: $I_{D_3,min} = 0A$

Max. Demagnetization Diode Current: $I_{D_3,max} = I_{mag}$

Min. Demagnetization Diode Voltage: $V_{D_3,min} = -2 \cdot V_{in}$

Max. Demagnetization Diode Voltage: $V_{D_3,max} = V_f$

Demagnetization Diode Voltage after t_d: $V_{D_3,t_{ad}} = -V_{in}$

Demagnetization Diode Voltage during t_3: $V_{D_3,t_3} = -V_{in}$

12.8. Rectifier Diode D_1

12.8.1. CCM & DCM.

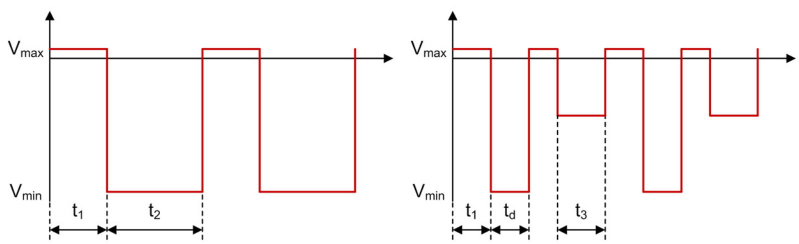


Figure 12.8.1. **Single Switch Forward - Rectifier Diode D_1 Voltage Waveforms in CCM and DCM**

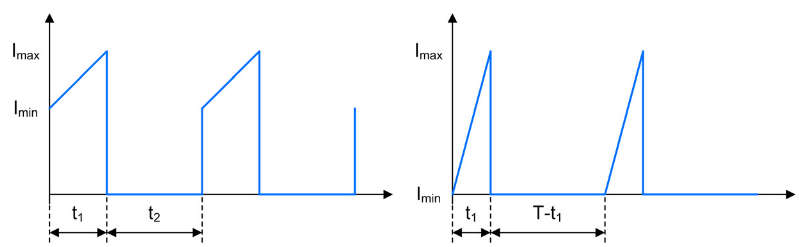


Figure 12.8.2. **Single Switch Forward - Rectifier Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

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

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

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

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

12.9. Freewheeling Diode D_2

12.8.1. CCM & DCM.

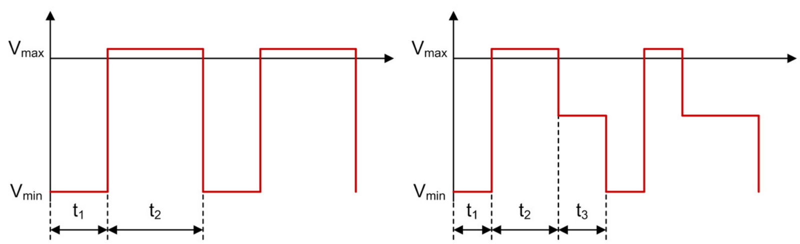


Figure 12.9.1. **Single Switch Forward - Freewheeling Diode D_2 Voltage Waveforms in CCM and DCM**

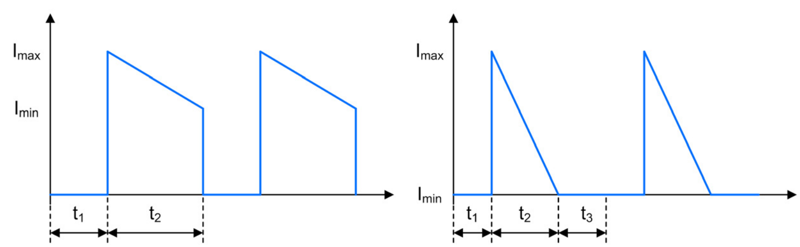


Figure 12.9.2. **Single Switch Forward - Freewheeling Diode D_2 Current Waveforms in CCM and DCM**

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

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

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

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: $V_{D_2,t_3} = -V_{out}$

12.10. Input Capacitor C_i

12.10.1. CCM & DCM.

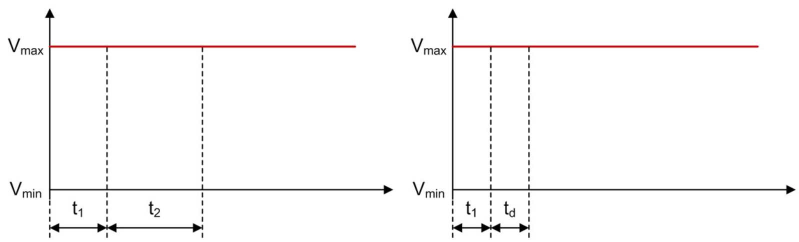


Figure 12.10.1. **Single Switch Forward - Input Capacitor C_i VoltageWaveforms in CCM and DCM**

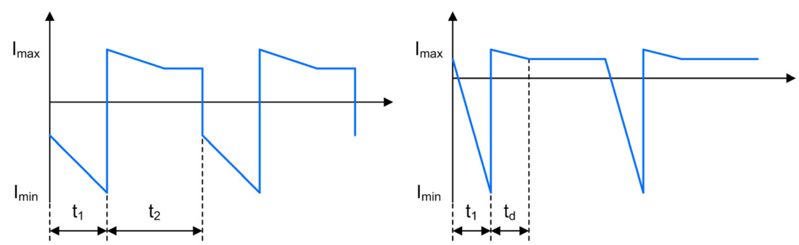


Figure 12.10.2. **Single Switch Forward - Input Capacitor C_i Current Waveforms in CCM and DCM**

Min. Input Capacitor Current during t_1: $I_{C_i,min,t_1} = I_{N_p,avg} - I_{pri,max} - I_{D_3,avg}$

Max. Input Capacitor Current during t_1: $I_{C_i,max,t_1} = I_{N_p,avg} - I_{pri,min} - I_{D_3,avg}$

Min. Input Capacitor Current during t_d: $I_{C_i,min,t_d} = I_{N_p,avg} - I_{D_3,avg}$

Max. Input Capacitor Current during t_d: $I_{C_i,max,t_d} = I_{N_p,avg} - I_{D_3,avg} + I_{mag}$

Input Capacitor Current after t_d: $I_{C_i,t_{ad}} = I_{N_p,avg} - I_{D_3,avg}$

Input Capacitor Current during t_3: $I_{C_i,t_3} = I_{N_p,avg} - I_{D_3,avg}$

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

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

12.11. Output Capacitor C_o

12.11.1. CCM & DCM.

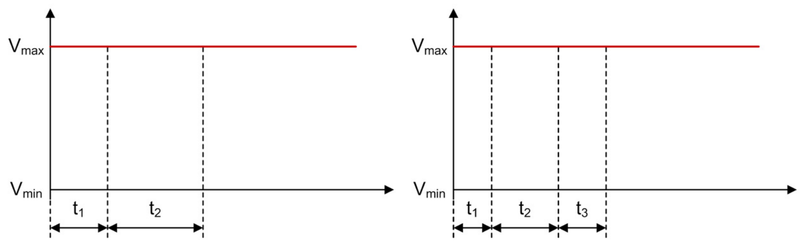


Figure 12.11.1. **Single Switch Forward - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

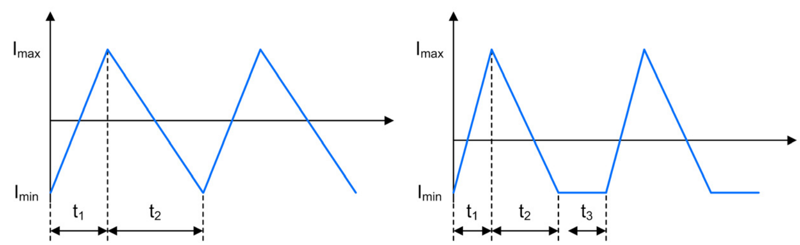


Figure 12.11.2. **Single Switch Forward - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

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

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

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

CHAPTER 13

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.

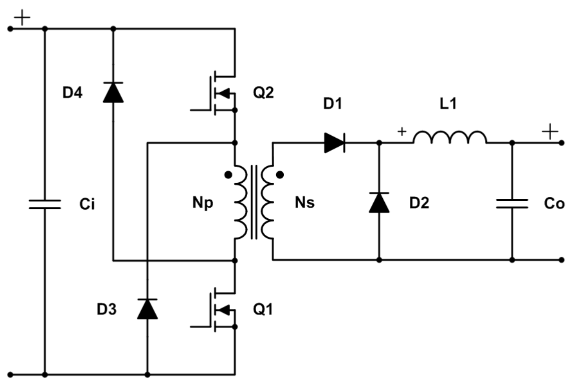


Figure 13.0.1. **Schematic of a Two Switch Forward converter**

13.1. General

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

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:	$t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{f_{switch} \cdot \left(V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}\right) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$
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.

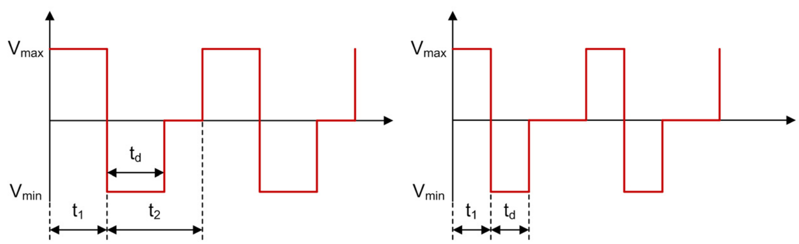


Figure 13.2.1. **Two Switch Forward - Primary Side Transformer Winding N_p Voltage Waveforms in CCM and DCM**

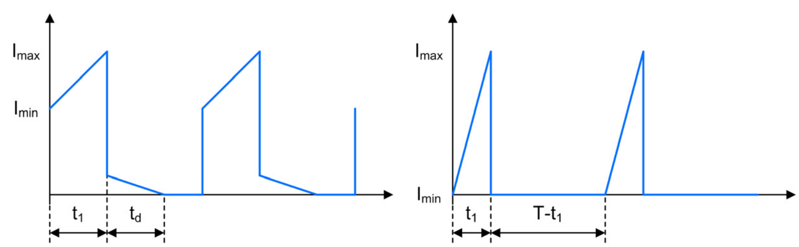


Figure 13.2.2. **Two Switch Forward - Primary Side Transformer Winding N_p Current Waveforms in CCM and DCM**

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

Min. Primary Transformer Current during t_1: $I_{N_p,min,t_1} = I_{pri,min}$

Max. Primary Transformer Current during t_1: $I_{N_p,max,t_1} = I_{pri,max}$

Min. Primary Transformer Current during t_2: $I_{N_p,min,t_2} = 0V$

Max. Primary Transformer Current during t_2: $I_{N_p,max,t_2} = I_{mag}$

Min. Primary Transformer Voltage: $V_{N_p,min} = -V_{in} - 2 \cdot V_f$

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

13.3. Secondary Side Transformer Winding N_s

13.3.1. CCM & DCM.

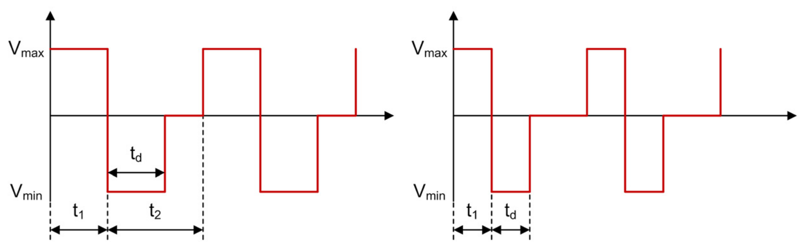


Figure 13.3.1. **Two Switch Forward - Secondary Side Transformer Winding N_s VoltageWaveforms in CCM and DCM**

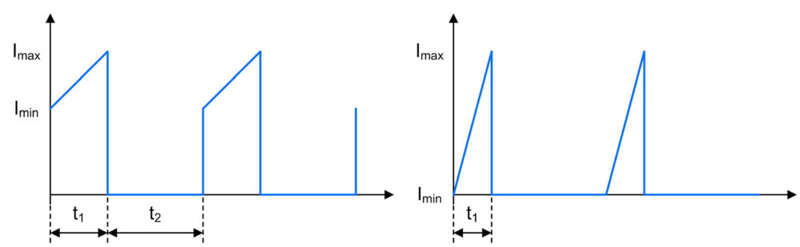


Figure 13.3.2. **Two Switch Forward - Secondary Side Transformer Winding N_s Current Waveforms in CCM and DCM**

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: $V_{N_s,min} = -\left(V_{in} + 2 \cdot V_f\right) \cdot \frac{n_s}{n_p}$

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.

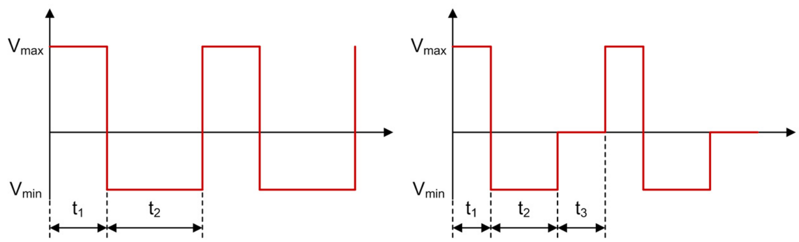


Figure 13.4.1. **Two Switch Forward - Inductor L_1 Voltage Waveforms in CCM and DCM**

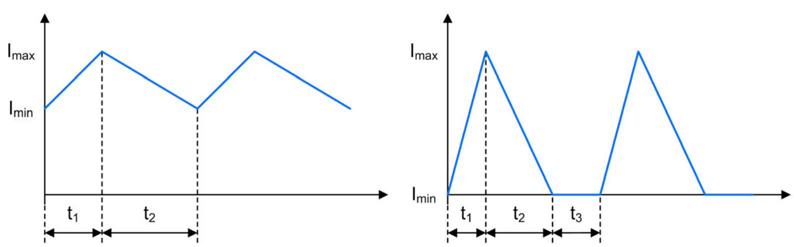


Figure 13.4.2. **Two Switch Forward - Inductor L_1 Current Waveforms in CCM and DCM**

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.

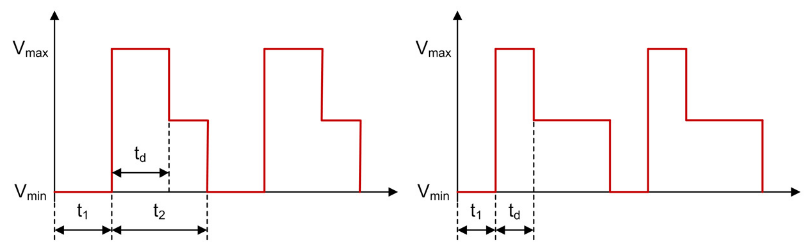


Figure 13.5.1. **Two Switch Forward - FET Q_1/Q_2 Voltage Waveforms in CCM and DCM**

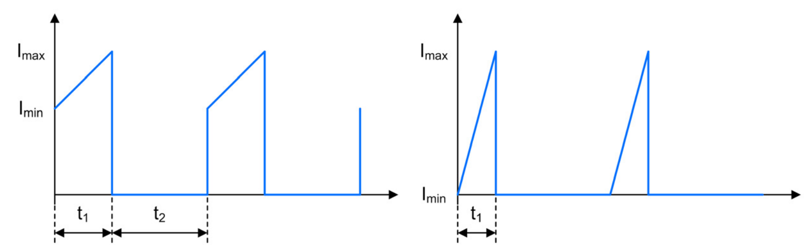


Figure 13.5.2. **Two Switch Forward - FET Q_1/Q_2 Current Waveforms in CCM and DCM**

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: $\mathrm{V}_{Q_1,t_{ad}} = \frac{1}{2} \cdot V_{in}$

FET Voltage during t_3: $\mathrm{V}_{Q_{1/2},t_3} = \frac{1}{2} \cdot V_{in}$

13.6. Demagnetization Diode D_3/D_4

13.6.1. CCM & DCM.

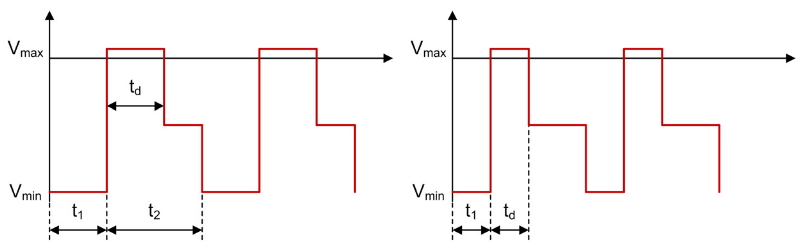


Figure 13.6.1. **Two Switch Forward - Demagnetization Diode D_3/D_4 Voltage Waveforms in CCM and DCM**

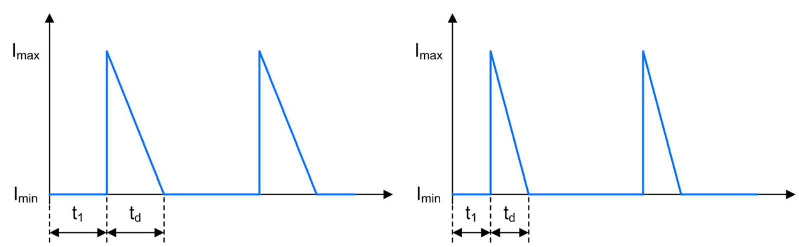


Figure 13.6.2. **Two Switch Forward - Demagnetization Diode D_3/D_4 Current Waveforms in CCM and DCM**

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.

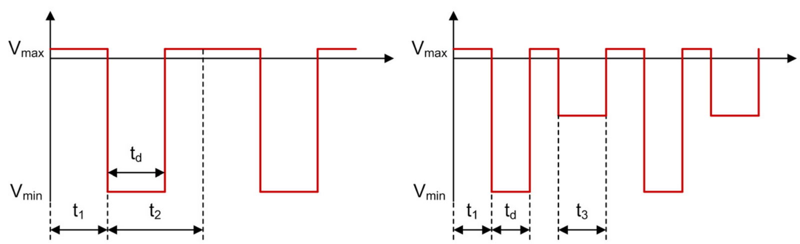


Figure 13.7.1. **Two Switch Forward - Rectifier Diode D_1 Voltage Waveforms in CCM and DCM**

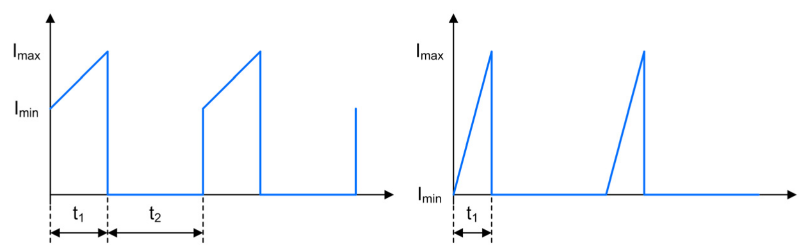


Figure 13.7.2. **Two Switch Forward - Rectifier Diode D_1 Current Waveforms in CCM and DCM**

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

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

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

Min. Rectifier Diode Voltage: $V_{D_1,min} = -(V_{in} + 2 \cdot V_f) \cdot \frac{n_s}{n_p} + V_f$

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

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

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

13.8. Freewheeling Diode D_2

13.8.1. CCM & DCM.

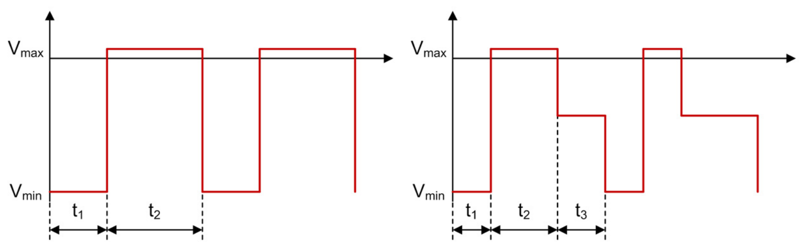


Figure 13.8.1. **Two Switch Forward - Freewheeling Diode D_2 Voltage Waveforms in CCM and DCM**

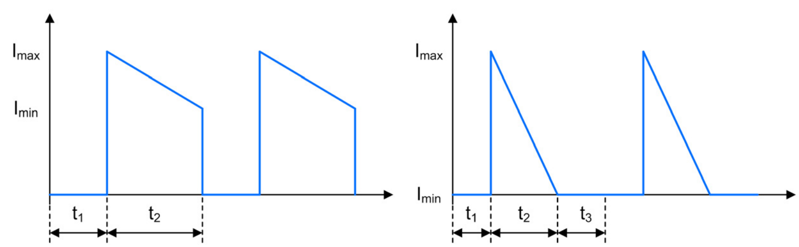


Figure 13.8.2. **Two Switch Forward - Freewheeling Diode D_2 Current Waveforms in CCM and DCM**

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.

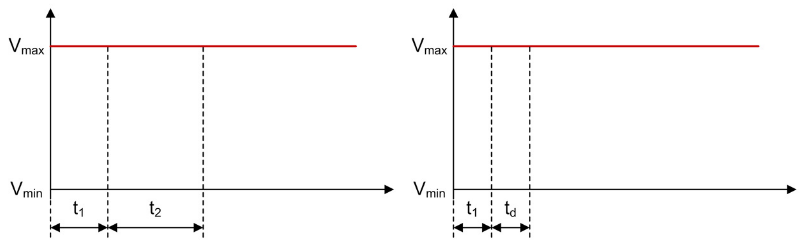


Figure 13.9.1. **Two Switch Forward - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

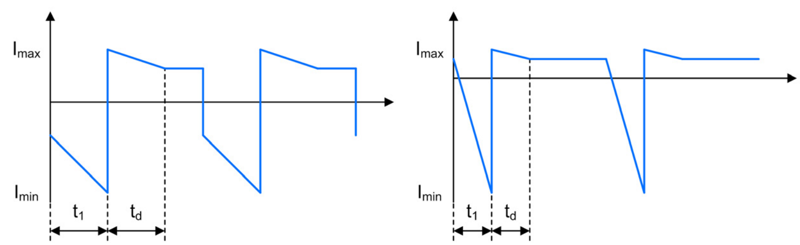


Figure 13.9.2. **Two Switch Forward - Input Capacitor C_i Current Waveforms in CCM and DCM**

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.

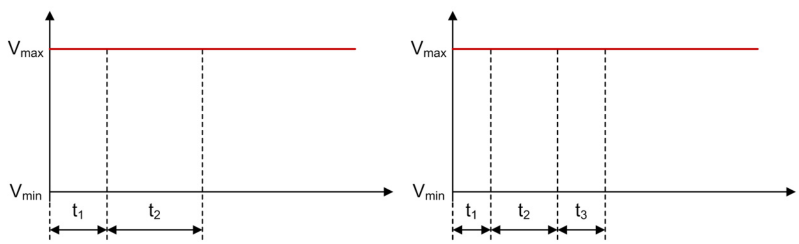


Figure 13.10.1. **Two Switch Forward - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

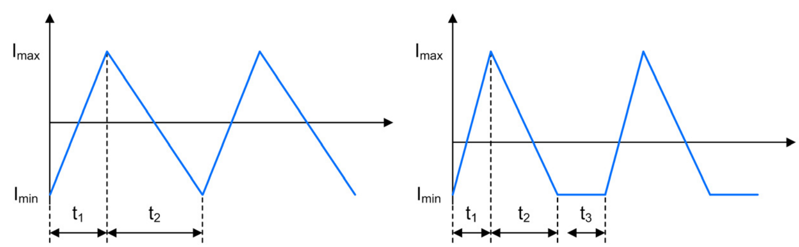


Figure 13.10.2. **Two Switch Forward - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

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

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

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

CHAPTER 14

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.

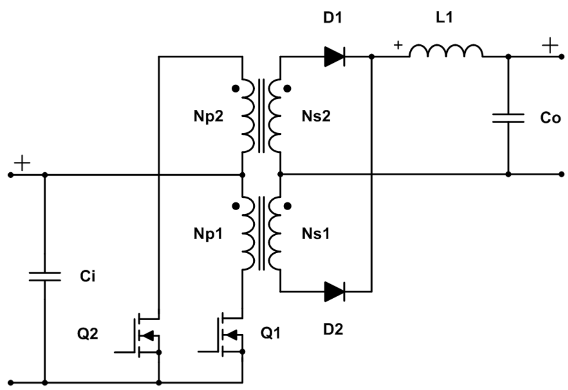


Figure 14.0.1. **Schematic of a Push-Pull converter**

14.1. General

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

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

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: $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{2 \cdot f_{switch} \cdot \left(V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}\right) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$

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.

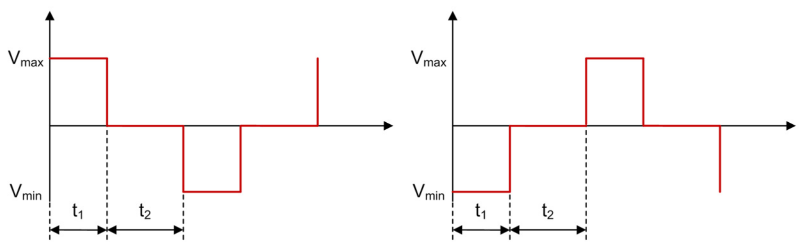


Figure 14.2.1. **Push-Pull - Primary Side Transformer Windings N_{p1} and N_{p2} Voltage Waveforms in CCM**

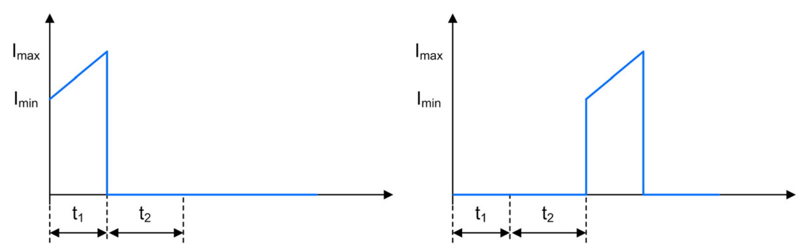


Figure 14.2.2. **Push-Pull - Primary Side Transformer Windings N_{p1} and N_{p2} Current Waveforms in CCM**

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.

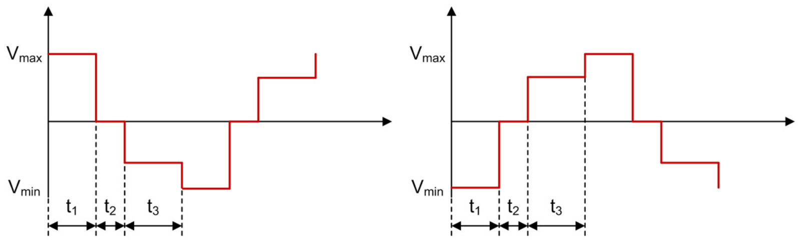


Figure 14.2.3. **Push-Pull - Primary Side Transformer Windings N_{p1} and N_{p2} Voltage Waveforms in DCM**

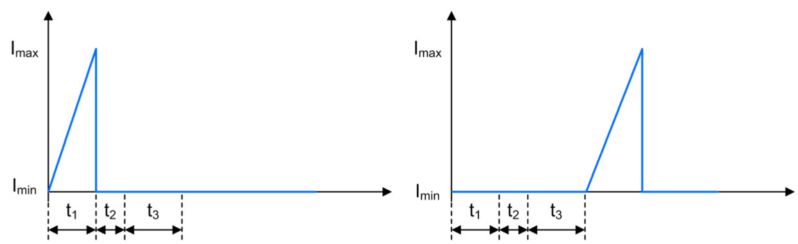


Figure 14.2.4. **Push-Pull - Primary Side Transformer Windings N_{p1} and N_{p2} Current Waveforms in DCM**

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.

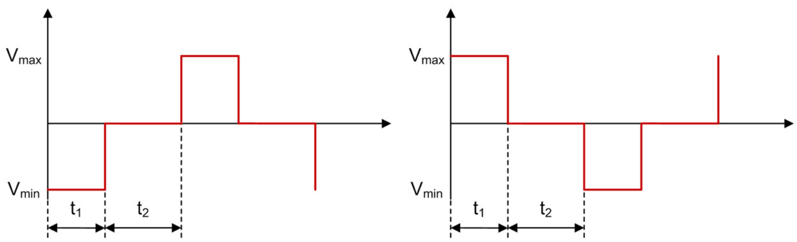


Figure 14.3.1. **Push-Pull - Secondary Side Transformer Windings N_{s1} and N_{s2} Voltage Waveforms in CCM**

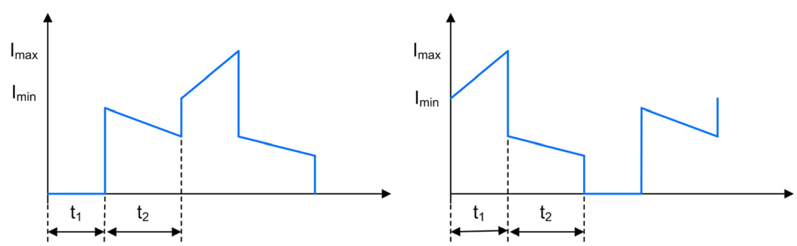


Figure 14.3.2. **Push-Pull - Secondary Side Transformer Windings N_{s1} and N_{s2} Current Waveforms in CCM**

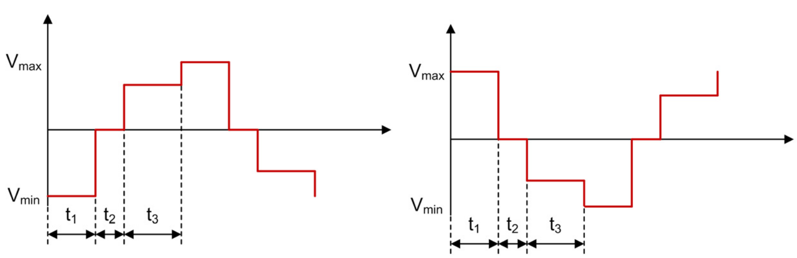


Figure 14.3.3. **Push-Pull - Secondary Side Transformer Windings N_{s1} and N_{s2} Voltage Waveforms in DCM**

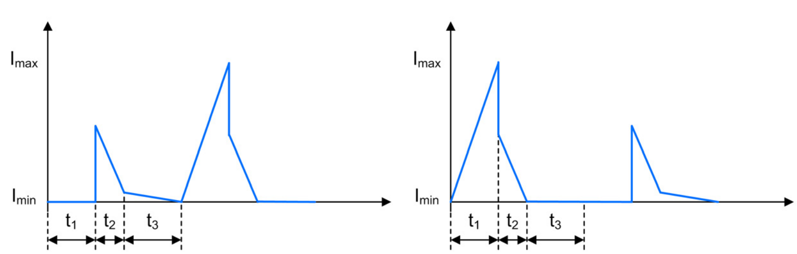


Figure 14.3.4. **Push-Pull - Secondary Side Transformer Windings N_{s1} and N_{s2} Current Waveforms in DCM**

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.

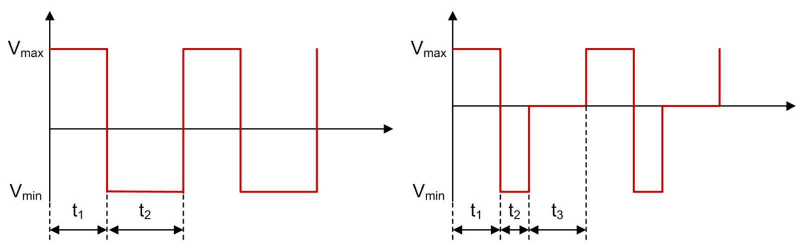


Figure 14.4.1. **Push-Pull - Inductor L_1 Voltage Waveforms in CCM and DCM**

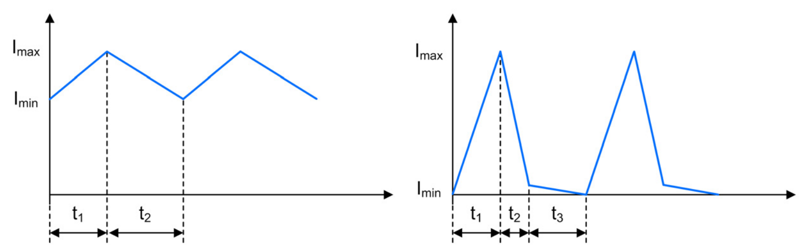


Figure 14.4.2. **Push-Pull - Inductor L_1 Current Waveforms in CCM and DCM**

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.

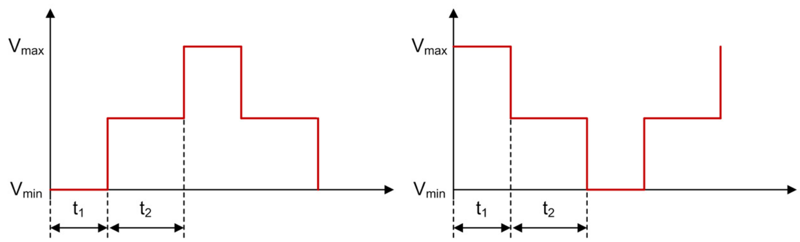


Figure 14.5.1. **Push-Pull - FETs Q_1 and Q_2 Voltage Waveforms in CCM**

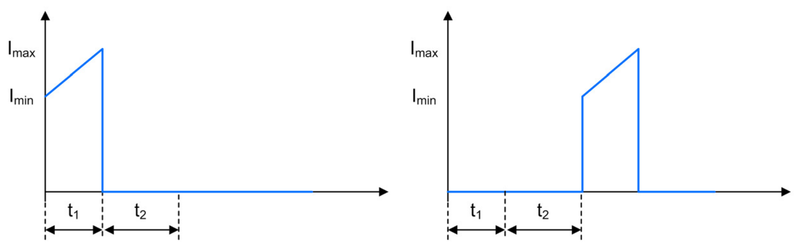


Figure 14.5.2. **Push-Pull - FETs Q_1 & Q_2 Current Waveforms in CCM**

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.

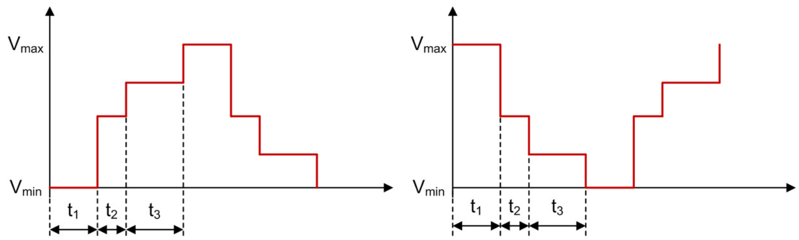


Figure 14.5.3. **Push-Pull - FETs Q_1 and Q_2 Voltage Waveforms in DCM**

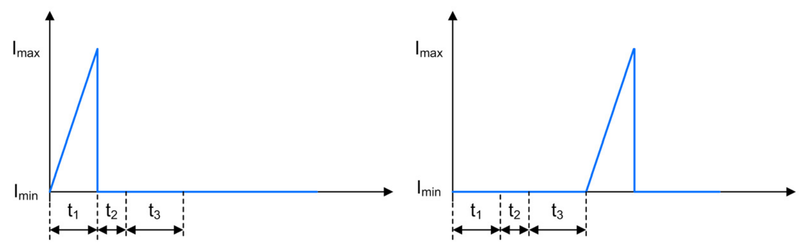


Figure 14.5.4. **Push-Pull - FETs Q_1 and Q_2 Current Waveforms in DCM**

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.

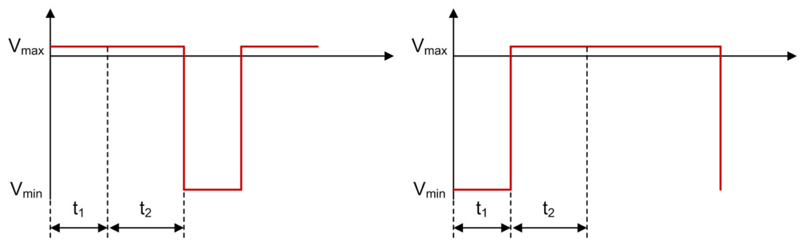


Figure 14.6.1. **Push-Pull - Rectifier Diodes D_1 and D_2 Voltage Waveforms in CCM**

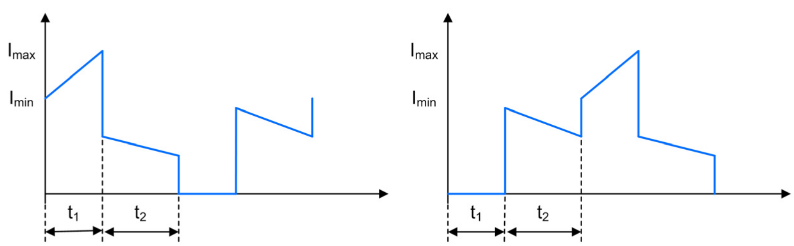


Figure 14.6.2. **Push-Pull - Rectifier Diodes D_1 and D_2 Current Waveforms in CCM**

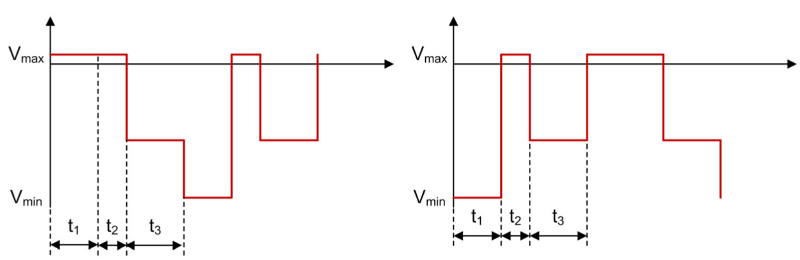


Figure 14.6.3. **Push-Pull - Rectifier Diodes D_1 and D_2 Voltage Waveforms in DCM**

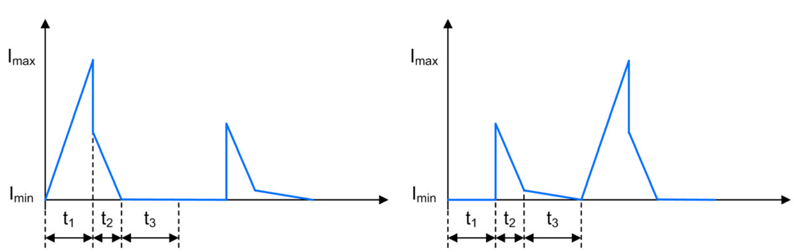


Figure 14.6.4. **Push-Pull - Rectifier Diodes D_1 and D_2 Current Waveforms in DCM**

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.

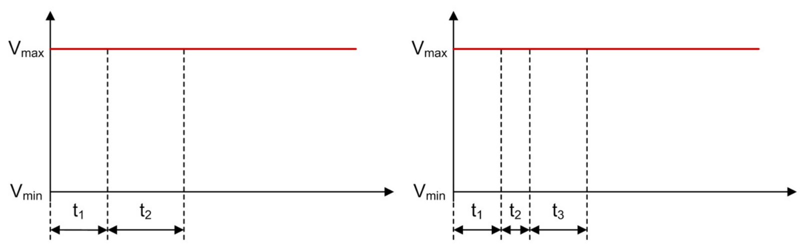


Figure 14.7.1. **Push-Pull - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

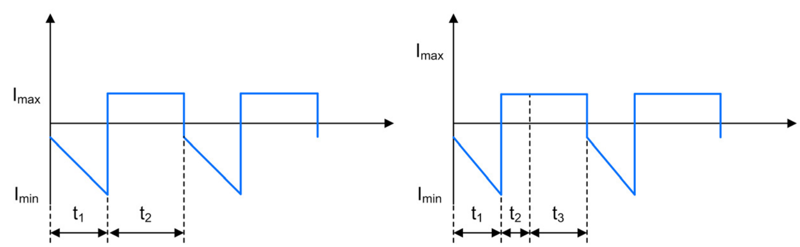


Figure 14.7.2. **Push-Pull - Input Capacitor C_i Current Waveforms in CCM and DCM**

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.

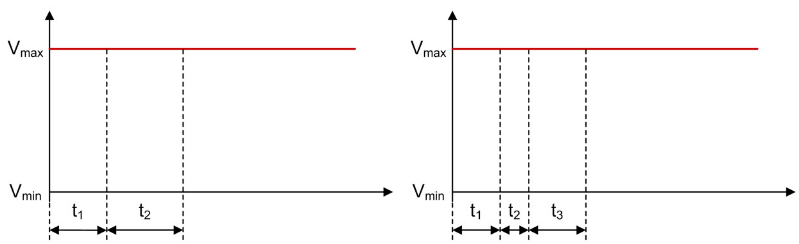


Figure 14.8.1. **Push-Pull - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

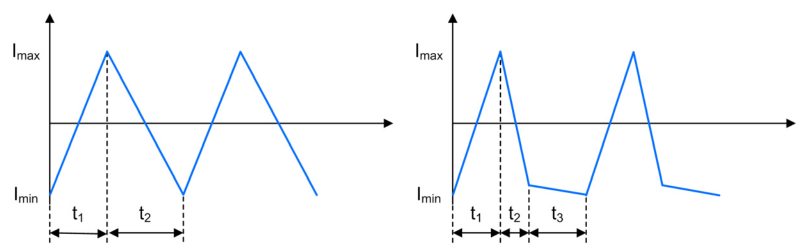


Figure 14.8.2. **Push-Pull - Output Capacitor C_o Current Waveforms in CCM and DCM**

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.

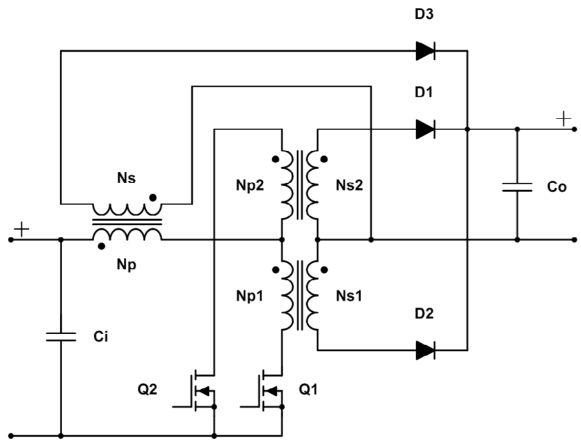


Figure 15.0.1. **Schematic of a Weinberg converter**

15.1. General

Secondary Side Inductance (Push-Pull): $L_{s,pushpull} = \frac{L_{p,pushpull}}{(\frac{n_P}{n_S})^2}$

Secondary Side Inductance (Flyback): $L_{s,flyback} = \frac{L_{p,flyback}}{(\frac{n_P}{n_S})^2}$

Inductor Current Ripple: $I_{ripple} = \frac{(V_{in} - (V_{out} + V_f) \cdot \frac{n_P}{n_S}) \cdot t_1}{L_{p,flyback}}$

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.

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: $t_2 = \frac{1}{2 \cdot f_{switch}} - t_1$

Average Input Pulse Current: $I_{in,pulse,avg} = \frac{(V_{out} + V_f) \cdot I_{out}}{V_{in}} \cdot \frac{1}{2 \cdot D}$

Min. Primary Current: $I_{pri,min} = I_{in,pulse,avg} - \frac{I_{ripple}}{2}$

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.

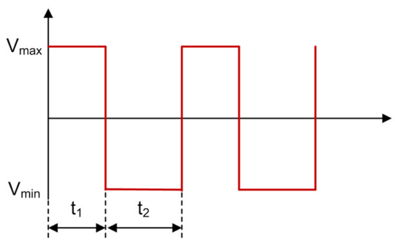


Figure 15.2.1. **Weinberg - Primary Side Flyback Inductor N_p Voltage Waveform in CCM**

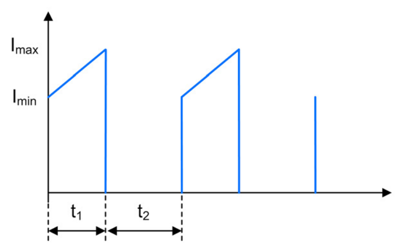


Figure 15.2.2. **Weinberg - Primary Side Flyback Inductor N_p Current Waveform in CCM**

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: $V_{N_pi,max} = V_{in} - (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

15.3. Secondary Side Flyback Inductor N_s

15.3.1. CCM.

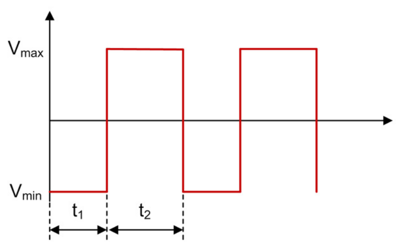


Figure 15.3.1. **Weinberg - Secondary Side Flyback Inductor N_s Voltage Waveform in CCM**

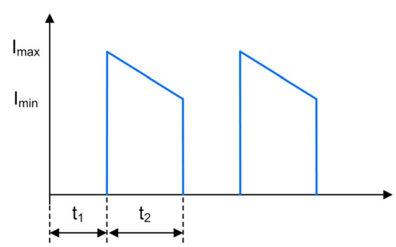


Figure 15.3.2. **Weinberg - Secondary Side Flyback Inductor N_s Current Waveform in CCM**

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

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

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

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

Max. Secondary Flyback Transformer Voltage: $V_{N_s,max} = -V_{N_p,min} \cdot \frac{n_s}{n_p}$

15.4. Primary Side Push-Pull Transformer Windings N_{p1} & N_{p2}

15.4.1. CCM.

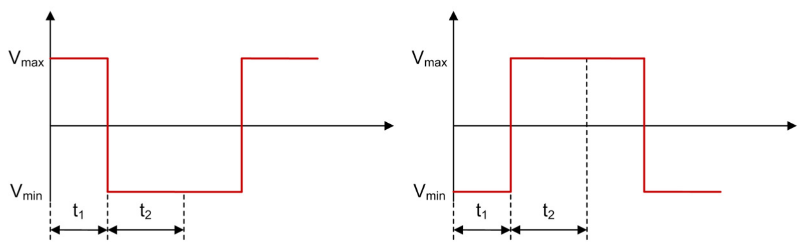


Figure 15.4.1. **Weinberg - Primary Side Push-Pull Transformer Windings N_{p1} and N_{p2} Voltage Waveforms in CCM**

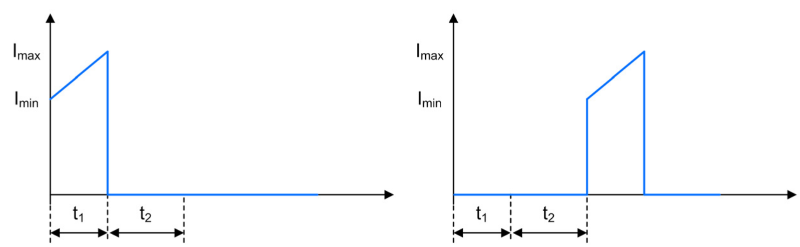


Figure 15.4.2. **Weinberg - Primary Side Push-Pull Transformer Windings N_{p1} and N_{p2} Current Waveforms in CCM**

Average Primary Push-Pull Transformer Current: $I_{N_{p1/p2},avg} = \frac{I_{pri,min}+I_{pri,max}}{2} \cdot t_1 \cdot f_{switch}$

Min. Primary Push-Pull Transformer Current: $I_{N_{p1/p2},min} = I_{pri,min}$

Max. Primary Push-Pull Transformer Current: $I_{N_{p1/p2},max} = I_{pri,max}$

Min. Primary Push-Pull Transformer Voltage: $V_{N_{p1/p2},min} = -\left(V_{out} + V_f\right) \cdot \frac{n_p}{n_s}$

Max. Primary Push-Pull Transformer Voltage: $V_{N_{p1/p2},max} = \left(V_{out} + V_f\right) \cdot \frac{n_p}{n_s}$

15.5. Secondary Side Push-Pull Transformer Windings N_{s1} & N_{s2}

15.5.1. CCM.

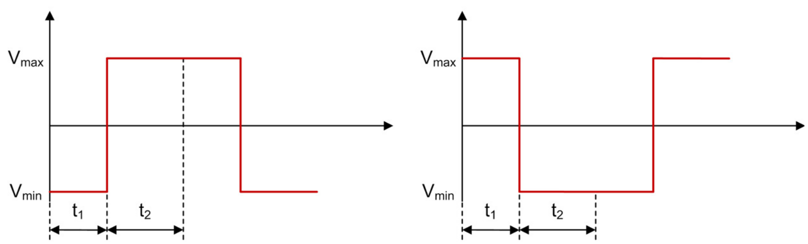


Figure 15.5.1. **Weinberg - Secondary Side Push-Pull Transformer Windings N_{s1} and N_{s2} Voltage Waveforms in CCM**

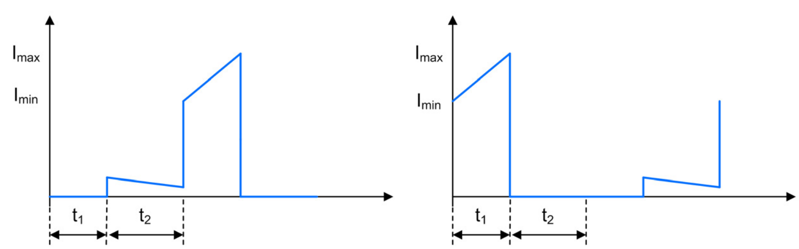


Figure 15.5.2. **Weinberg - Secondary Side Push-Pull Transformer Windings N_{s1} and N_{s2} Current Waveforms in CCM**

Min. Secondary Push-Pull Transformer Current during t_1: $I_{N_{s1/s2},min,t_1} = (I_{pri,min} + \frac{(1-D)\cdot I_{mag}}{2}) \cdot \frac{n_p}{n_s}$

Max. Secondary Push-Pull Transformer Current during t_1: $I_{N_{s1/s2},max,t_1} = (I_{pri,min} - \frac{(1+D)\cdot I_{mag}}{2}) \cdot \frac{n_p}{n_s}$

Min. Secondary Push-Pull Transformer Current during t_2: $I_{N_{s1/s2},min,t_2} = I_{N_{s1/s2},min,t_1} - I_{N_s,min}$

Max. Secondary Push-Pull Transformer Current during t_2: $I_{N_{s1/s2},max,t_2} = I_{N_{s1/s2},max,t_1} - I_{N_s,min}$

Average Secondary Push-Pull Transformer Current:

$$I_{N_{s1/s2},avg} = \frac{I_{N_{s1/s2},min,t_1}+I_{N_{s1/s2},max,t_1}}{2} \cdot t_1 \cdot f_{switch} + \frac{I_{N_{s1/s2},min,t_2}+I_{N_{s1/s2},max,t_2}}{2} \cdot t_2 \cdot f_{switch}$$

Min. Secondary Push-Pull Transformer Voltage: $V_{N_{s1/s2},min} = V_{N_{p1/p2},min} \cdot \frac{n_s}{n_p}$

Max. Secondary Push-Pull Transformer Voltage: $V_{N_{s1/s2},max} = V_{N_{p1/p2},max} \cdot \frac{n_s}{n_p}$

15.6. FET Q_1 & Q_2

15.6.1. CCM.

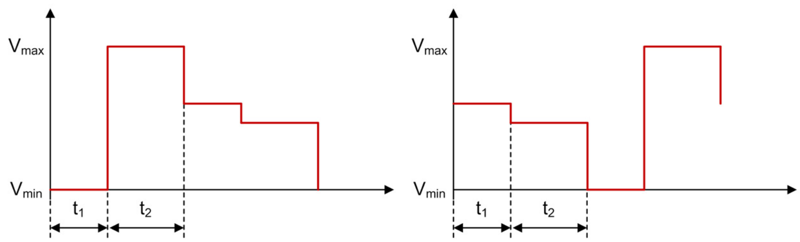


Figure 15.6.1. **Weinberg - FET Q_1 and Q_2 Voltage Waveforms in CCM**

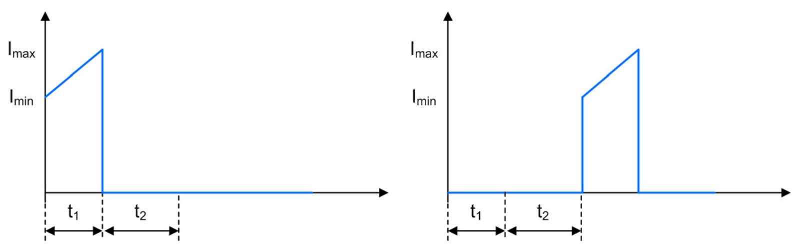


Figure 15.6.2. **Weinberg - FET Q_1 and Q_2 Current Waveforms in CCM**

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.

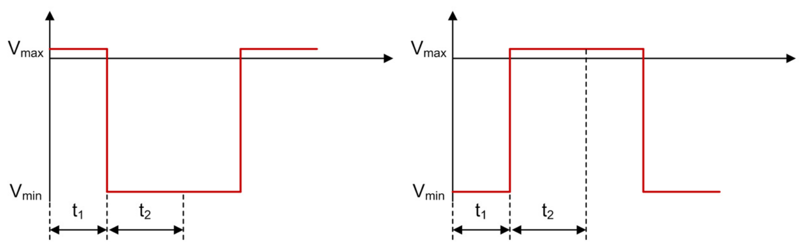


Figure 15.7.1. **Weinberg - Push-Pull Rectifier Diodes D_1 and D_2 Voltage Waveforms in CCM**

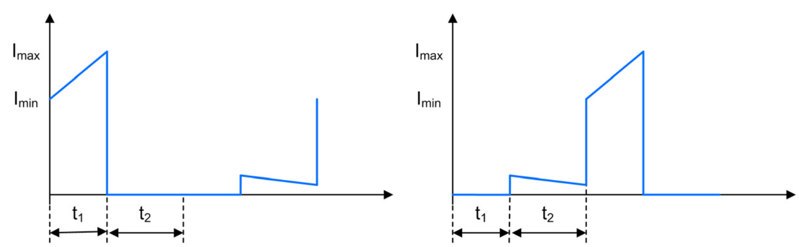


Figure 15.7.2. **Weinberg - Push-Pull Rectifier Diodes D_1 and D_2 Current Waveforms in CCM**

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.

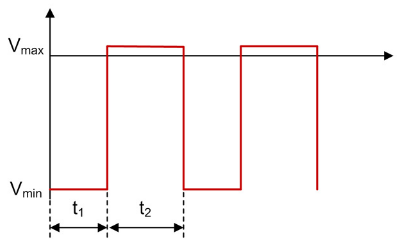


Figure 15.8.1. **Weinberg - Flyback Demagnetization Diode D_3 Voltage Waveform in CCM**

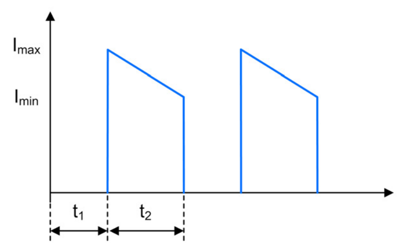


Figure 15.8.2. **Weinberg - Flyback Demagnetization Diode D_3 Current Waveform in CCM**

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.

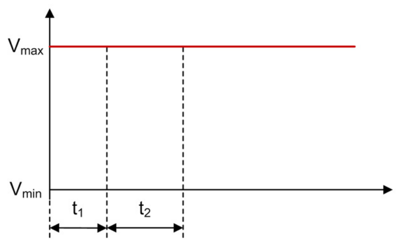


Figure 15.9.1. **Weinberg - Input Capacitor C_i Voltage Waveform in CCM**

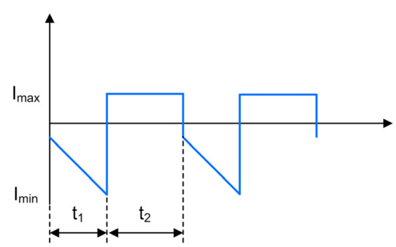


Figure 15.9.2. **Weinberg - Input Capacitor C_i Current Waveform in CCM**

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.

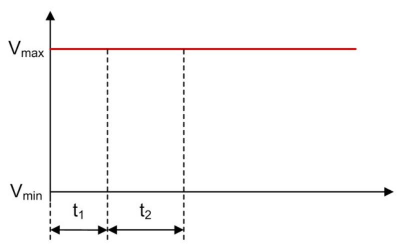


Figure 15.10.1. **Weinberg - Output Capacitor C_o Voltage Waveform in CCM**

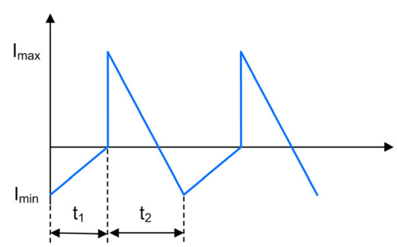


Figure 15.10.2. **Weinberg - Output Capacitor C_o Current Waveform in CCM**

Min. Output Capacitor Current during t_1:	$I_{C_o,min,t_1} = I_{D_{1/2},min,t_1} - I_{out}$
Max. Output Capacitor Current during t_1:	$I_{C_o,max,t_1} = I_{D_{1/2},max,t_1} - I_{out}$
Min. Output Capacitor Current during t_2:	$I_{C_o,min,t_2} = I_{D_3,min,t_2} + I_{D_{1/2},min,t_2} - I_{out}$
Max. Output Capacitor Current during t_2:	$I_{C_o,max,t_2} = I_{D_3,max,t_2} + I_{D_{1/2},max,t_2} - I_{out}$
Average Output Capacitor Current:	$I_{C_o,avg} = 0A$
Output Capacitor Voltage:	$V_{C_o} = V_{out}$

CHAPTER 16

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.

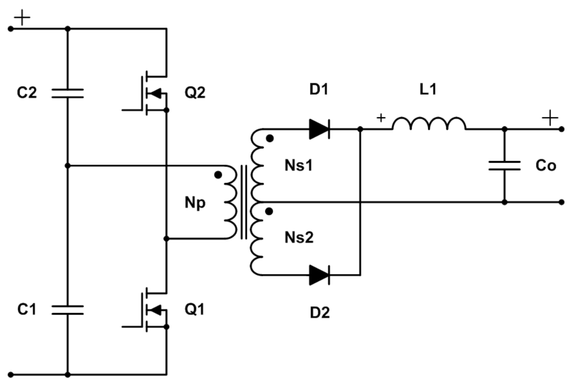


Figure 16.0.1. **Schematic of a Half-Bridge converter**

15.1. General

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

Inductor Current Ripple: $I_{ripple} = \frac{1}{L_1} \cdot (\frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}) \cdot t_1$

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: $t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{2 \cdot f_{switch} \cdot \left(\frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}\right) \cdot (\frac{1}{2} \cdot V_{in} \cdot \frac{n_s}{n_p})}}$

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.

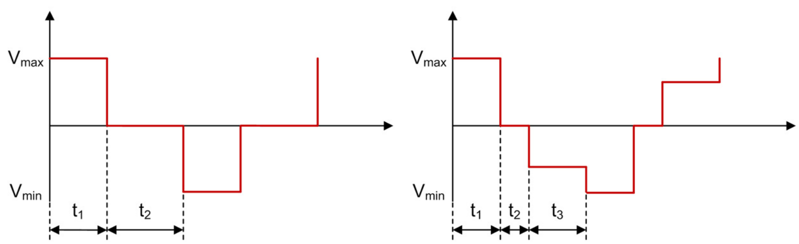


Figure 16.2.1. **Half-Bridge - Primary Side Transformer Winding N_p Voltage Waveforms in CCM and DCM**

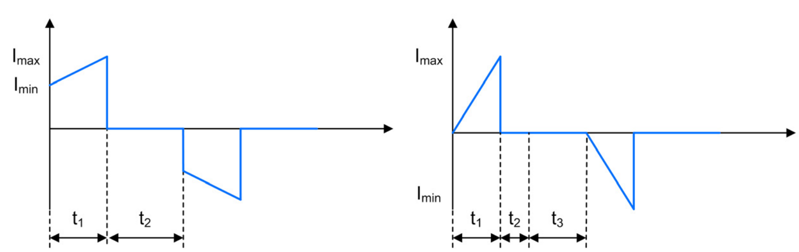


Figure 16.2.2. **Half-Bridge - Primary Side Transformer Winding N_p Current Waveforms in CCM and DCM**

Average Primary Transformer Current: $I_{N_p,avg} = 0A$

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: $V_{N_p,min} = -\frac{1}{2} \cdot V_{in}$

Max. Primary Transformer Voltage: $V_{N_p,max} = \frac{1}{2} \cdot V_{in}$

Min. Primary Transformer Voltage during t_3: $V_{N_p,t_3} = (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

16.3. Secondary Side Transformer Winding Ns_1 & Ns_2

16.3.1. CCM & DCM.

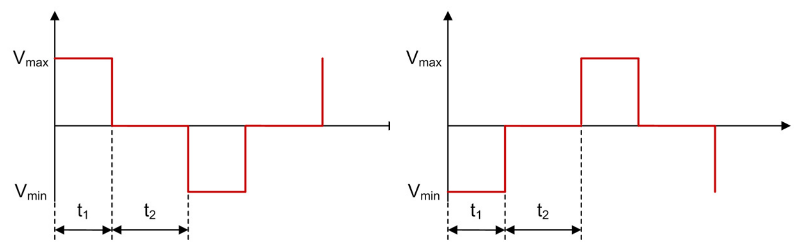


Figure 16.3.1. **Half-Bridge - Secondary Side Transformer Windings Ns_1 and Ns_2 Voltage Waveforms in CCM**

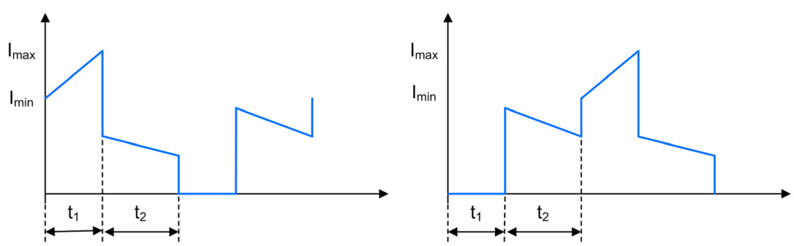


Figure 16.3.2. **Half-Bridge - Secondary Side Transformer Windings Ns_1 and Ns_2 Current Waveforms in CCM**

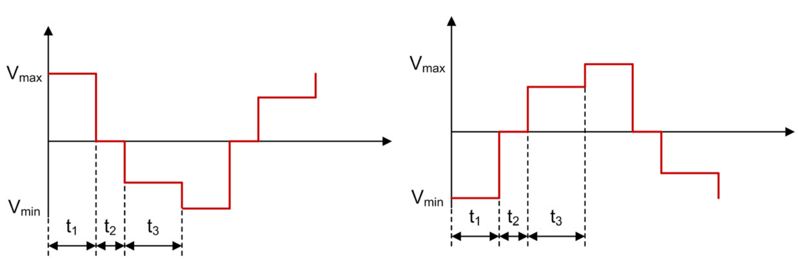


Figure 16.3.3. **Half-Bridge - Secondary Side Transformer Windings Ns_1 and Ns_2 Voltage Waveforms in DCM**

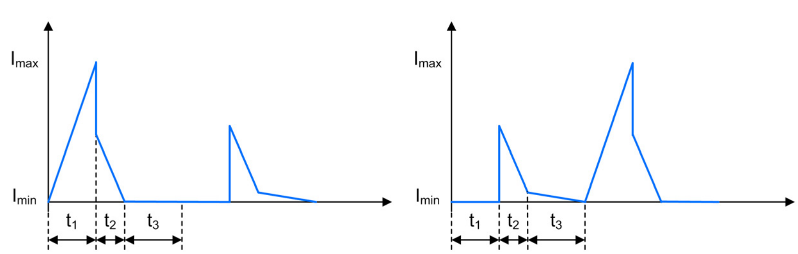


Figure 16.3.4. **Half-Bridge - Secondary Side Transformer Windings Ns_1 and Ns_2 Current Waveforms in DCM**

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:

$$I_{N_{s1/s2},avg} = f_{switch}\cdot\left(\frac{I_{sec,min}+I_{sec,max}}{2}\cdot t_1 + \frac{I_{N_{s1/s2},max,t_2}+I_{N_{s1/s2},min,t_2,other}}{2}\cdot t_2 + \frac{I_{N_{s1/s2},min,t_2}+I_{N_{s1/s2},max,t_2,other}}{2}\cdot t_2\right)$$

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.

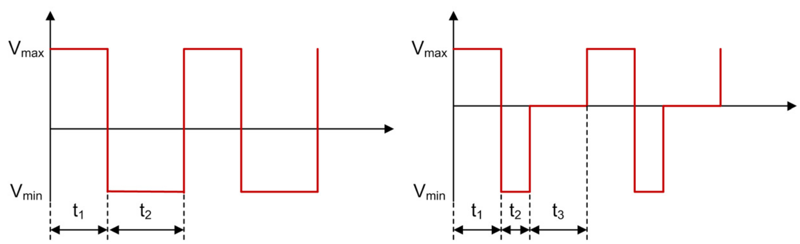


Figure 16.4.1. **Half-Bridge - Inductor L_1 Voltage Waveforms in CCM and DCM**

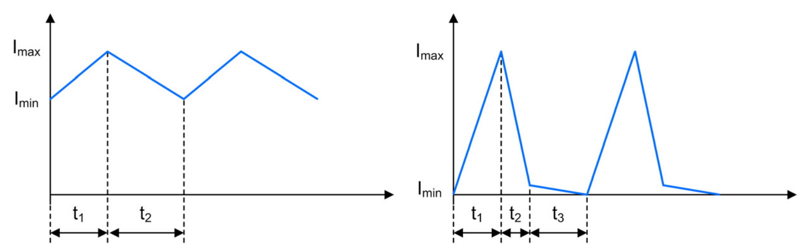


Figure 16.4.2. **Half-Bridge - Inductor L_1 Current Waveforms in CCM and DCM**

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.

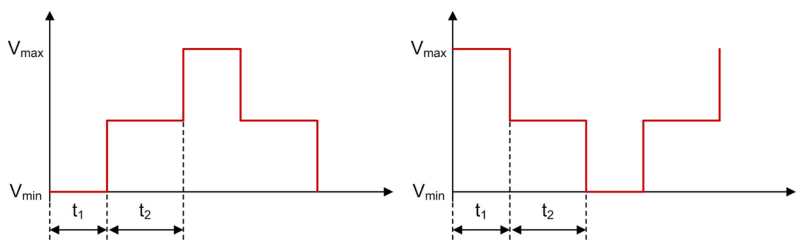


Figure 16.5.1. **Half-Bridge - FETs Q_1 and Q_2 Voltage Waveforms in CCM**

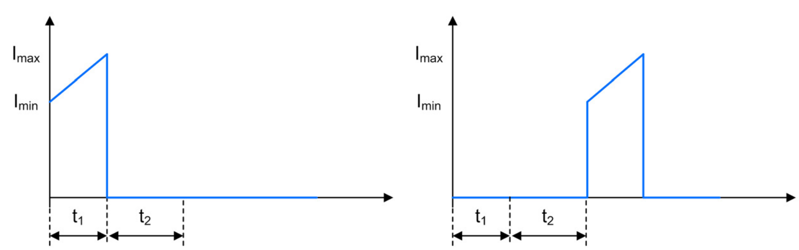


Figure 16.5.2. **Half-Bridge - FETs Q_1 and Q_2 Current Waveforms in CCM**

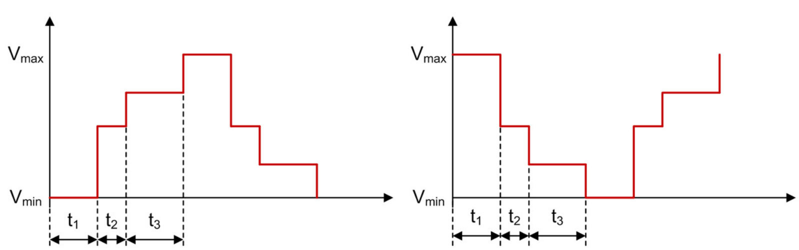


Figure 16.5.3. **Half-Bridge - FETs Q_1 and Q_2 Voltage Waveforms in DCM**

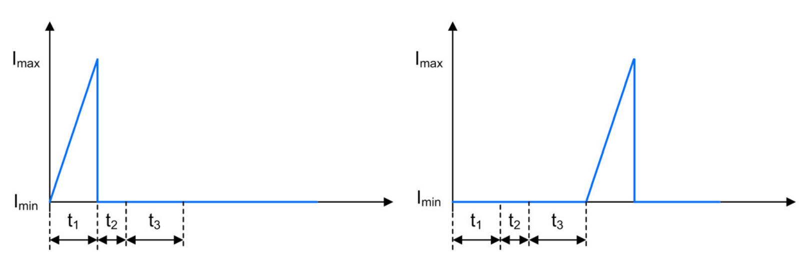


Figure 16.5.4. **Half-Bridge - FETs Q_1 and Q_2 Current Waveforms in DCM**

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: $\mathrm{V}_{Q_{1/2},min,t_3} = \frac{V_{in}}{2} - (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

Max. FET Voltage during t_3: $\mathrm{V}_{Q_{1/2},max,t_3} = \frac{V_{in}}{2} + (V_{out} + V_f) \cdot \frac{n_p}{n_s}$

16.6. Rectifier Diode D_1 & D_2

16.6.1. CCM & DCM.

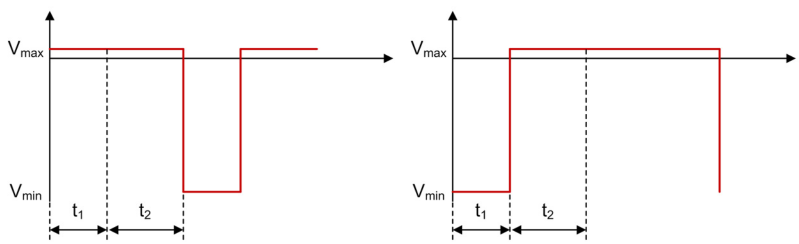


Figure 16.6.1. **Half-Bridge - Rectifier Diodes D_1 and D_2 Voltage Waveforms in CCM**

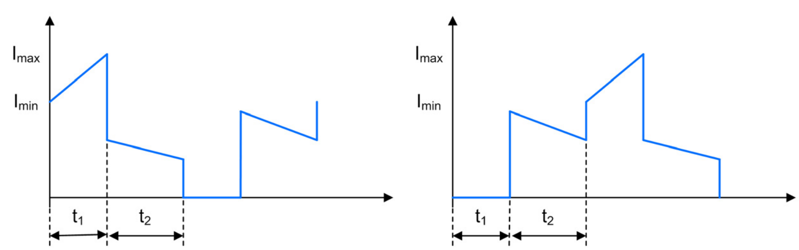


Figure 16.6.2. **Half-Bridge - Rectifier Diodes D_1 and D_2 Current Waveforms in CCM**

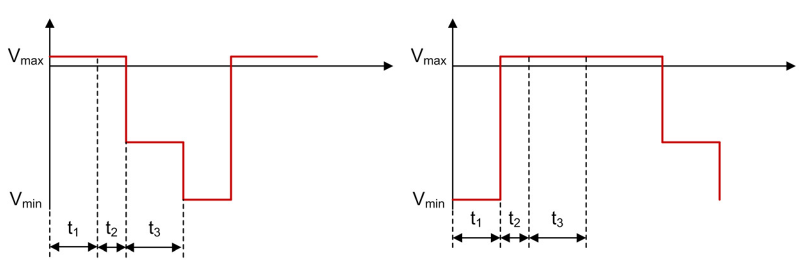


Figure 16.6.3. **Half-Bridge - Rectifier Diodes D_1 and D_2 Voltage Waveforms in DCM**

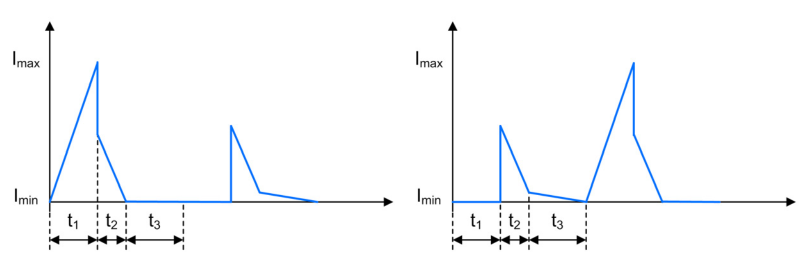


Figure 16.6.4. **Half-Bridge - Rectifier Diodes D_1 and D_2 Current Waveforms in DCM**

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.

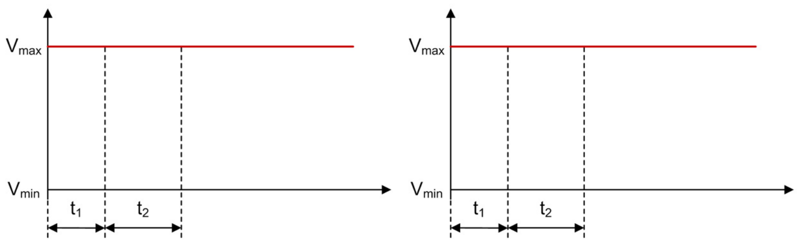


Figure 16.7.1. **Half-Bridge - Input Capacitor C_1 and C_2 Voltage Waveforms in CCM**

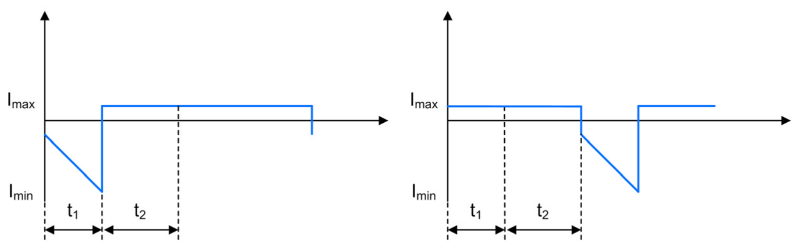


Figure 16.7.2. **Half-Bridge - Input Capacitor C_1 and C_2 Current Waveforms in CCM**

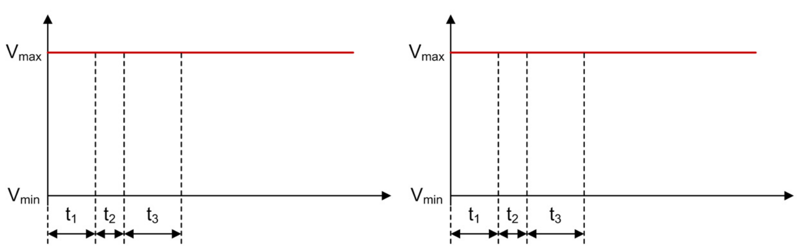


Figure 16.7.3. **Half-Bridge - Input Capacitor C_1 and C_2 Voltage Waveforms in DCM**

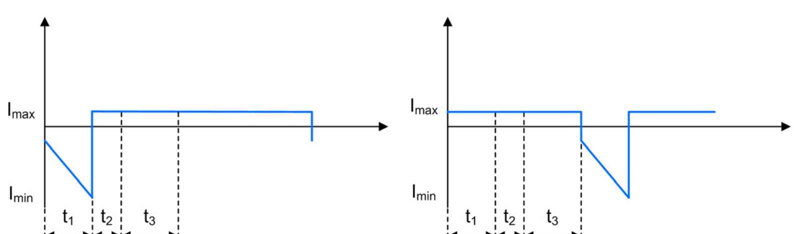


Figure 16.7.4. **Half-Bridge - Input Capacitor C_1 and C_2 Current Waveforms in DCM**

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: $V_{C_{1/2}} = \frac{V_{in}}{2}$

16.8. Output Capacitor C_o

16.8.1. CCM & DCM.

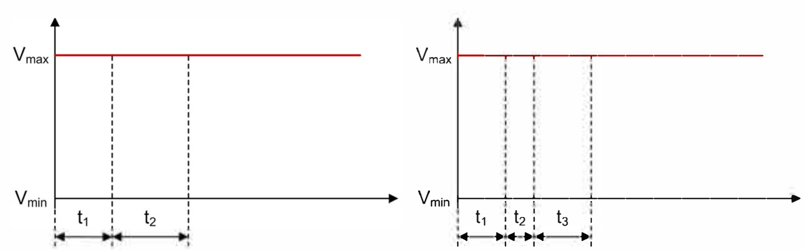


Figure 16.8.1. **Half-Bridge - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

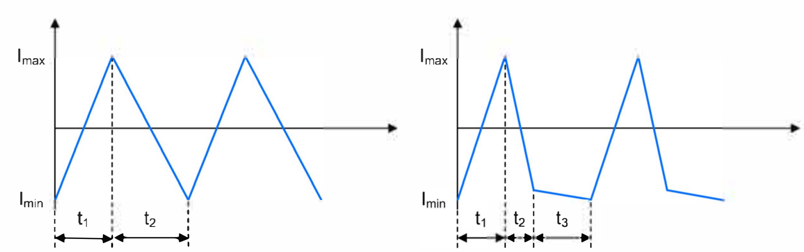


Figure 16.8.2. **Half-Bridge - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

CHAPTER 17

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.

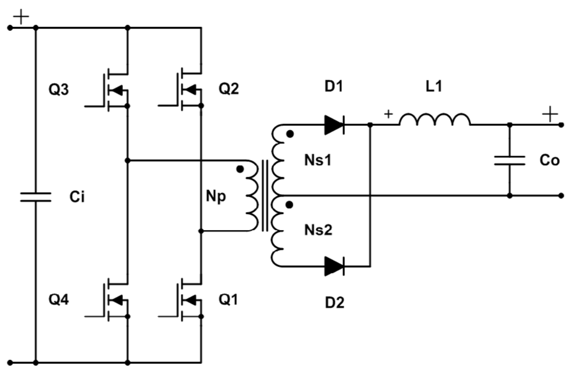


Figure 17.0.1. **Schematic of a Full-Bridge converter**

17.1. General

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

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

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:	$t_1 = \sqrt{2 \cdot I_{out} \cdot L_1 \cdot \frac{V_{out}+V_f}{2 \cdot f_{switch} \cdot \left(V_{in} \cdot \frac{n_s}{n_p} - V_f - V_{out}\right) \cdot (V_{in} \cdot \frac{n_s}{n_p})}}$
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.

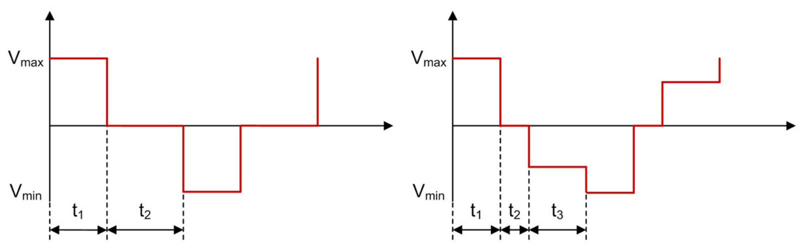


Figure 17.2.1. **Full-Bridge - Primary Side Transformer Winding N_p Voltage Waveforms in CCM and DCM**

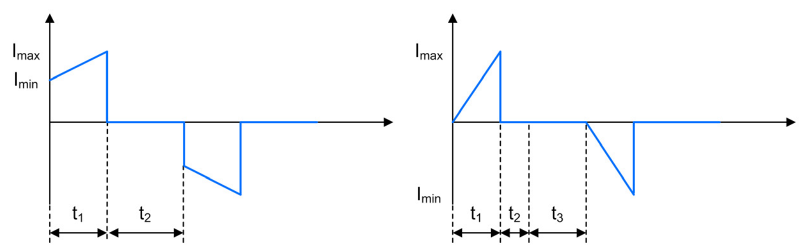


Figure 17.2.2. **Full-Bridge - Primary Side Transformer Winding N_p Current Waveforms in CCM and DCM**

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.

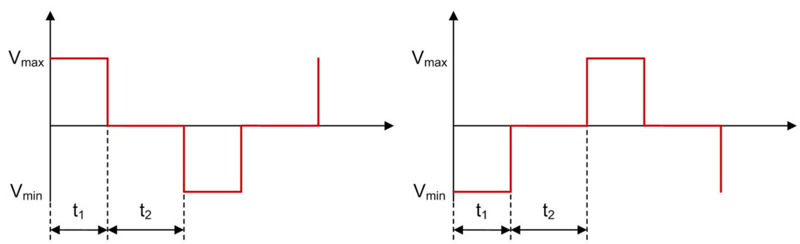


Figure 17.3.1. **Full-Bridge - Secondary Side Transformer Windings N_{s1} and N_{s2} Voltage Waveforms in CCM**

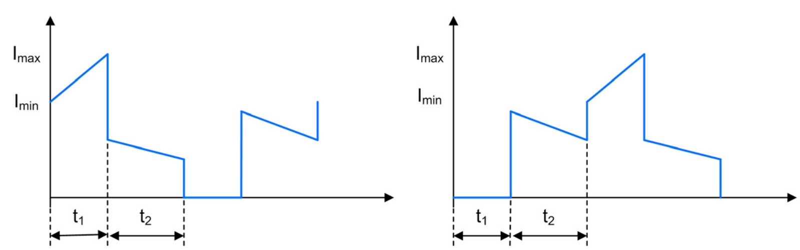


Figure 17.3.2. **Full-Bridge - Secondary Side Transformer Windings N_{s1} and N_{s2} Current Waveforms in CCM**

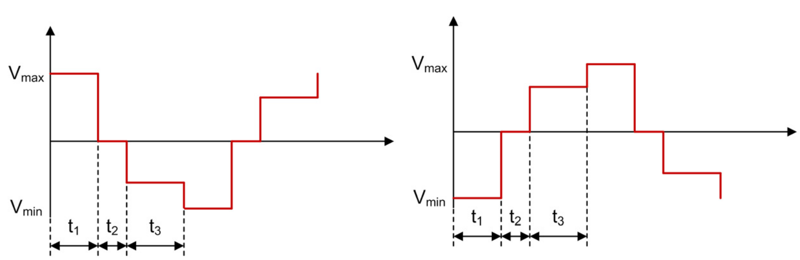


Figure 17.3.3. **Full-Bridge - Secondary Side Transformer Windings N_{s1} and N_{s2} Voltage Waveforms in DCM**

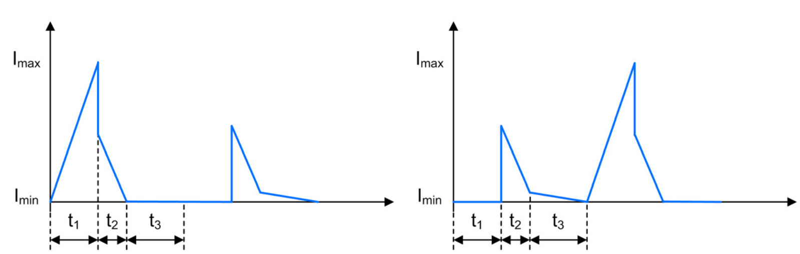


Figure 17.3.4. **Full-Bridge - Secondary Side Transformer Windings N_{s1} and N_{s2} Current Waveforms in DCM**

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): $I_{N_{s1/s2},min,t_2,other} = \frac{I_{pri,max}}{2 \cdot \frac{n_s}{n_p}} - \frac{I_{ripple}}{2}$

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 (t_3 of other FET): $I_{N_{s1/s2},min,t_3,other} = 0A$

Max. Secondary Transformer Current (t_3 of other FET): $I_{N_{s1/s2},max,t_3,other} = I_{N_{s1/s2},max,t_2,other} - I_{trans,sec,max,t_2}$

Secondary Transformer Current (t_3 of FET): $I_{N_{s1/s2},t_3} = 0A$

Average Secondary Current:

$$I_{N_{s1/s2},avg} = f_{switch} \cdot \left(\frac{I_{sec,min} + I_{sec,max}}{2} \cdot t_1 + \frac{I_{N_{s1/s2},max,t_2} + I_{N_{s1/s2},min,t_2,other}}{2} \cdot t_2 + \frac{I_{N_{s1/s2},min,t_2} + I_{N_{s1/s2},max,t_2,other}}{2} \cdot t_2 \right)$$

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: $V_{N_{s1/s2},max,t_3} = -V_{out} - V_f$

17.4. Inductor L_1

17.4.1. CCM & DCM.

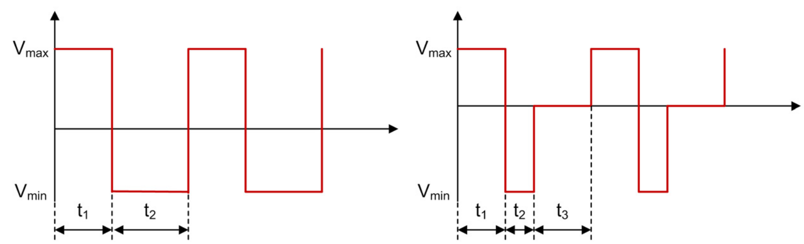


Figure 17.4.1. **Full-Bridge - Inductor L_1 Voltage Waveforms in CCM and DCM**

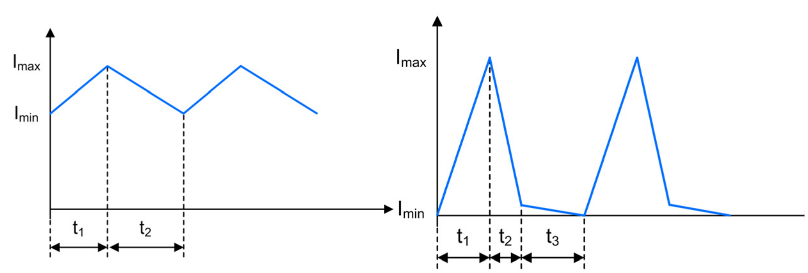


Figure 17.4.2. **Full-Bridge - Inductor L_1 Current Waveforms in CCM and DCM**

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

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

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

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

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

17.5. FET Q_1, Q_2, Q_3 & Q_4

17.5.1. CCM & DCM.

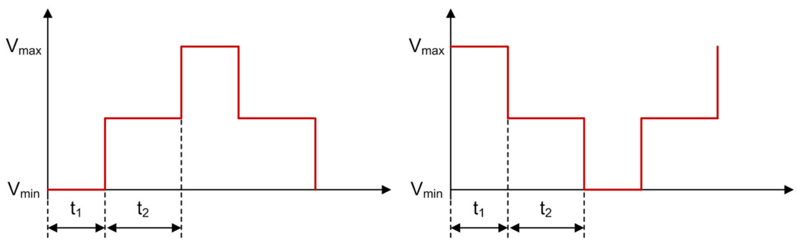


Figure 17.5.1. **Full-Bridge - FETs Q_1/Q_3 and Q_2/Q_4 Voltage Waveforms in CCM**

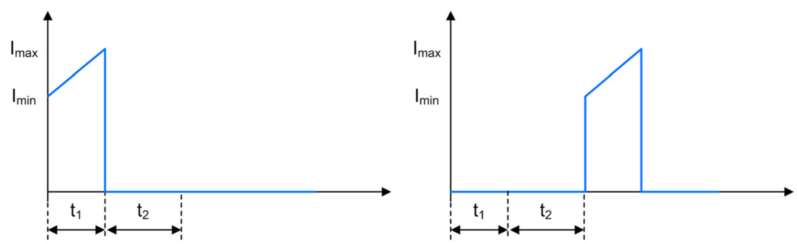


Figure 17.5.2. **Full-Bridge - FETs Q_1/Q_3 and Q_2/Q_4 Current Waveforms in CCM**

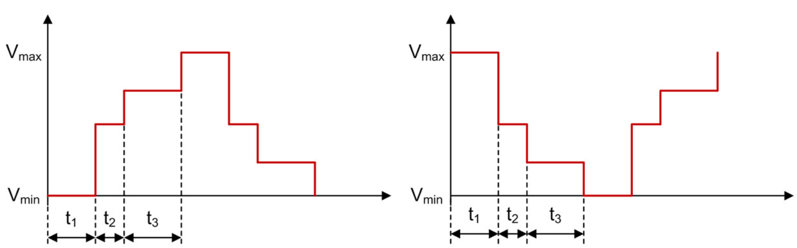


Figure 17.5.3. **Full-Bridge - FETs Q_1/Q_3 and Q_2/Q_4 Voltage Waveforms in DCM**

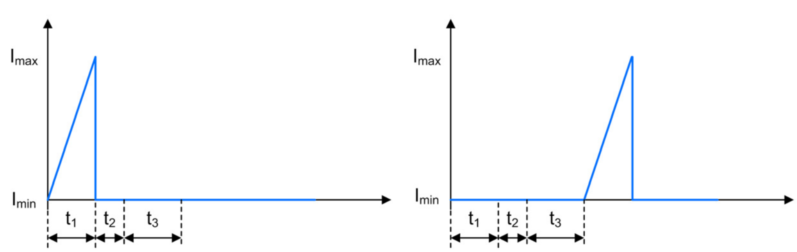


Figure 17.5.4. **Full-Bridge - FETs Q_1/Q_3 and Q_2/Q_4 Current Waveforms in DCM**

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.

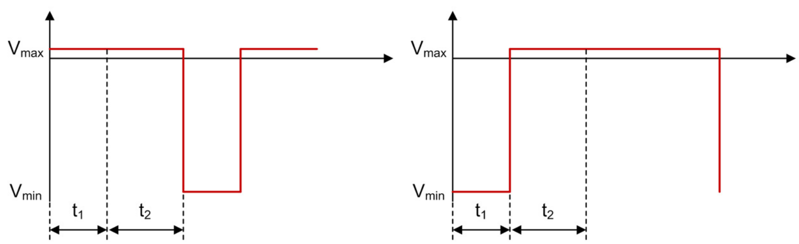


Figure 17.6.1. **Full-Bridge - Rectifier Diodes D_1 and D_2 Voltage Waveforms in CCM**

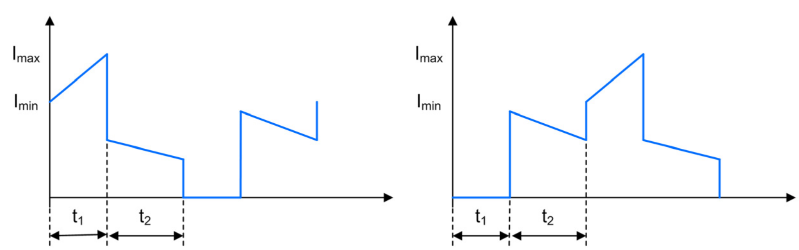


Figure 17.6.2. **Full-Bridge - Rectifier Diodes D_1 and D_2 Current Waveforms in CCM**

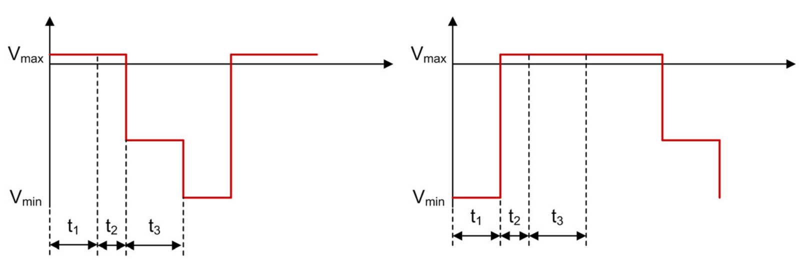


Figure 17.6.3. **Full-Bridge - Rectifier Diodes D_1 and D_2 Voltage Waveforms in DCM**

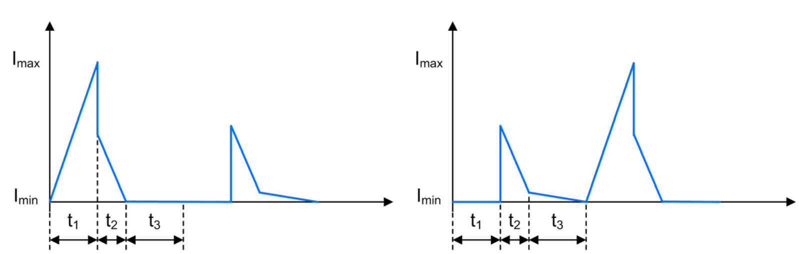


Figure 17.6.4. **Full-Bridge - Rectifier Diodes D_1 and D_2 Current Waveforms in DCM**

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):	$I_{D_{1/2},min,t_2,other} = I_{N_{s1/s2},min,t_2,other}$
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:	$V_{D_{1/2},min} = -2 \cdot V_{in} \cdot \frac{n_s}{n_p} + V_f$
Max. Rectifier Diode Voltage:	$V_{D_{1/2},max} = V_f$
Rectifier Diode Voltage during t_3:	$V_{D_{1/2},t_3} = -2 \cdot V_{out}$

17.7. Input Capacitor C_i

17.7.1. CCM & DCM.

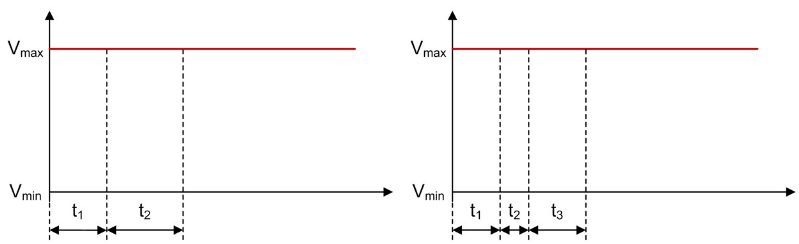


Figure 17.7.1. **Full-Bridge - Input Capacitor C_i Voltage Waveforms in CCM and DCM**

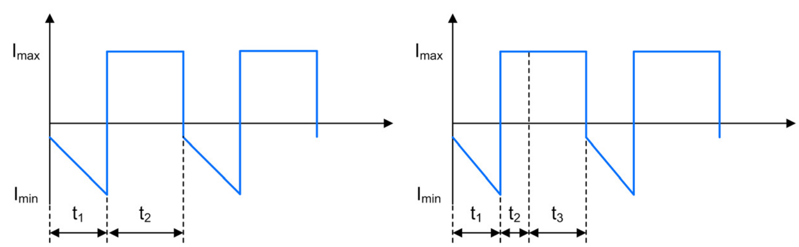


Figure 17.7.2. **Full-Bridge - Input Capacitor C_i Current Waveforms in CCM and DCM**

Min. Input Capacitor Current during t_1: $I_{C_i,min,t_1} = 2 \cdot I_{Q_{1/2/3/4},avg} - I_{pri,max}$

Max. Input Capacitor Current during t_1: $I_{C_i,max,t_1} = 2 \cdot I_{Q_{1/2/3/4},avg} - I_{pri,min}$

Input Capacitor Current during t_2 and t_3: $I_{C_i,t_{2/3}} = 2 \cdot I_{Q_{1/2/3/4},avg}$

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

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

17.8. Output Capacitor C_o

17.8.1. CCM & DCM.

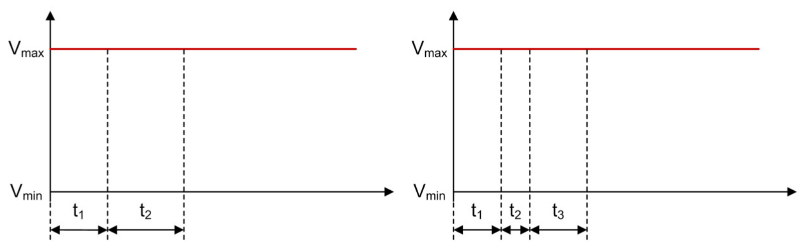


Figure 17.8.1. **Full-Bridge - Output Capacitor C_o Voltage Waveforms in CCM and DCM**

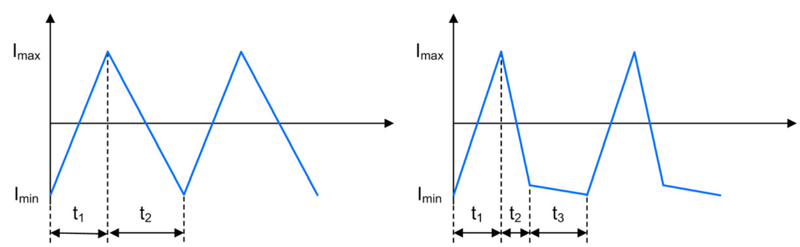


Figure 17.8.2. **Full-Bridge - Output Capacitor C_o Current Waveforms in CCM and DCM**

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

CHAPTER 18

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.

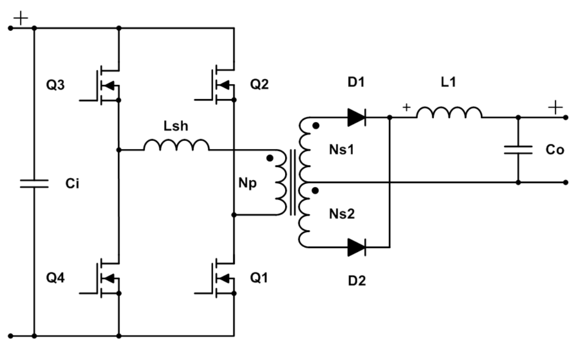


Figure 18.0.1. **Schematic of a Phase-Shifted Full-Bridge converter**

18.1. General

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

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.

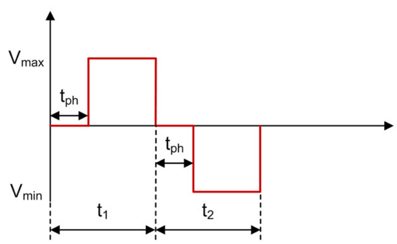


Figure 18.2.1. **Phase-Shifted Full-Bridge - Primary Side Transformer Winding N_p Voltage Waveform in CCM**

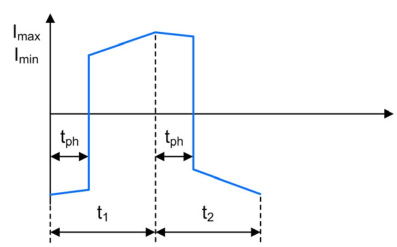


Figure 18.2.2. **Phase-Shifted Full-Bridge - Primary Side Transformer Winding N_p Current Waveform in CCM**

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.

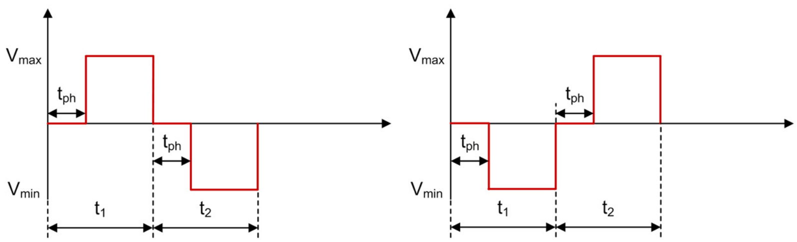


Figure 18.3.1. **Phase-Shifted Full-Bridge - Secondary Side Transformer Windings N_{s1} and N_{s2} Voltage Waveforms in CCM**

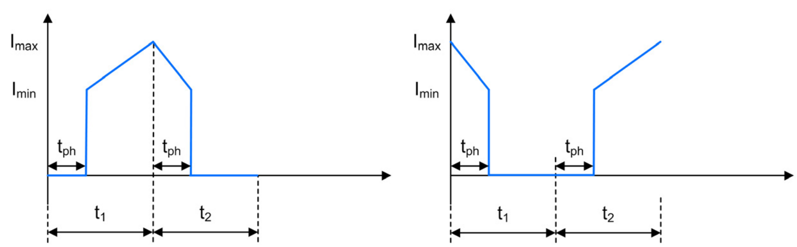


Figure 18.3.2. **Phase-Shifted Full-Bridge - Secondary Side Transformer Windings N_{s1} and N_{s2} Current Waveforms in CCM**

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:

$$I_{N_{s1/s2},avg} = f_{switch} \cdot (\frac{I_{N_{s1/s2},min}+I_{N_{s1/s2},max}}{2} \cdot (t_1 - t_{ph}) + \frac{I_{N_{s1/s2},max}+I_{N_{s1/s2},min}}{2} \cdot t_{ph})$$

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.

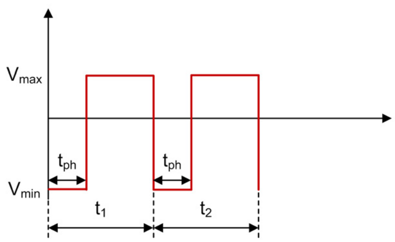


Figure 18.4.1. **Phase-Shifted Full-Bridge - Inductor L_1 Voltage Waveform in CCM**

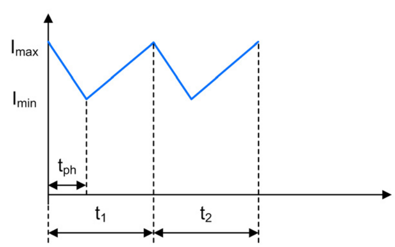


Figure 18.4.2. **Phase-Shifted Full-Bridge - Inductor L_1 Current Waveform in CCM**

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

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

18.5. FET Q_1, Q_2, Q_3 & Q_4

18.5.1. CCM.

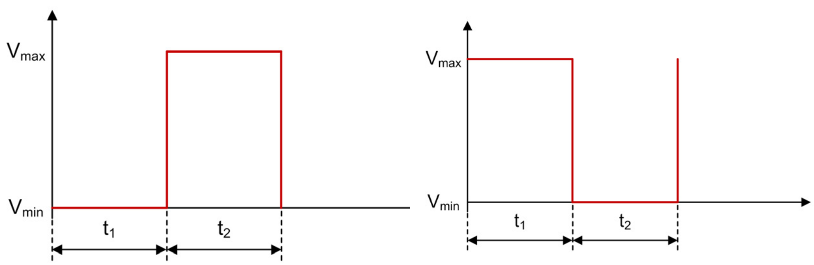


Figure 18.5.1. **Phase-Shifted Full-Bridge - FETs Q_1 and Q_2 Voltage Waveforms in CCM**

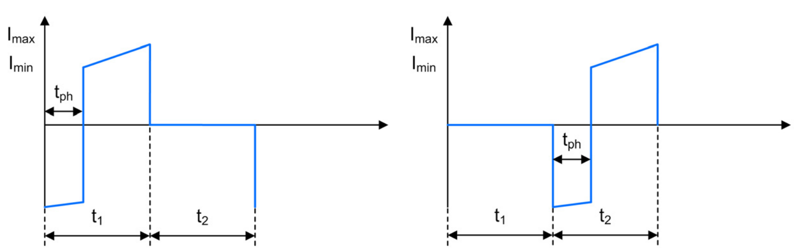


Figure 18.5.2. **Phase-Shifted Full-Bridge - FETs Q_1 and Q_2 Current Waveforms in CCM**

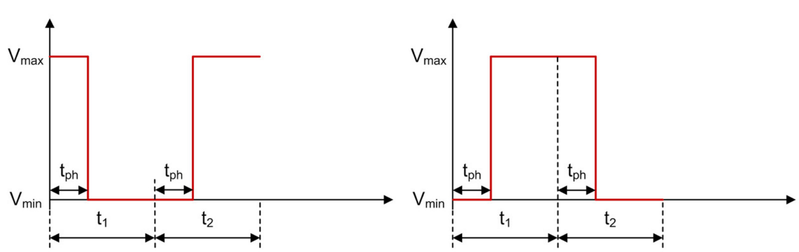


Figure 18.5.3. **Phase-Shifted Full-Bridge - FETs Q_3 and Q_4 Voltage Waveforms in CCM**

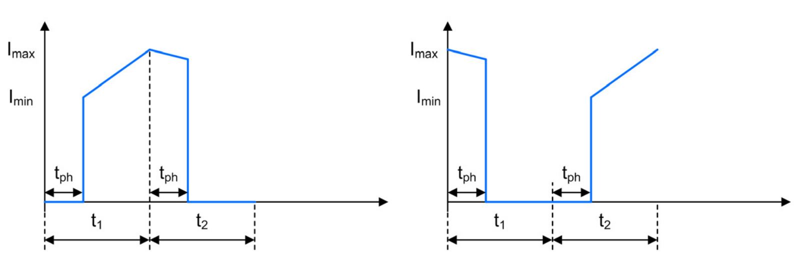


Figure 18.5.4. **Phase-Shifted Full-Bridge - FETs Q_3 and Q_4 Current Waveforms in CCM**

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.

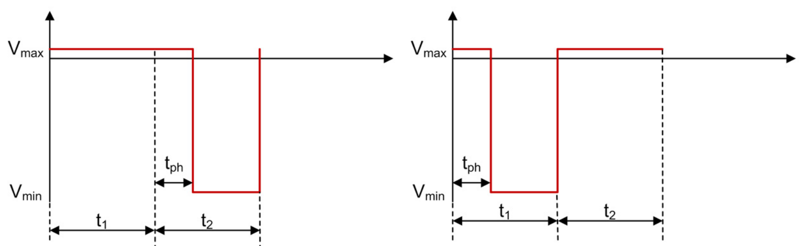


Figure 18.6.1. **Phase-Shifted Full-Bridge - Rectifier Diodes D_1 and D_2 Voltage Waveforms in CCM**

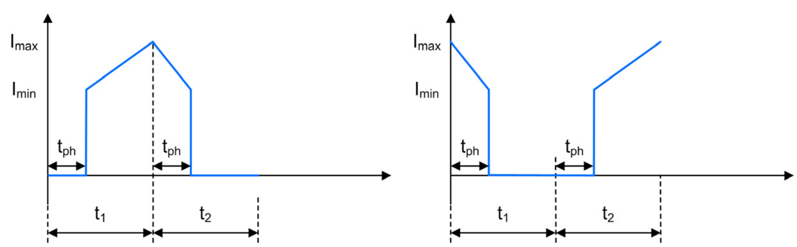


Figure 18.6.2. **Phase-Shifted Full-Bridge - Rectifier Diodes D_1 and D_2 Current Waveforms in CCM**

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.

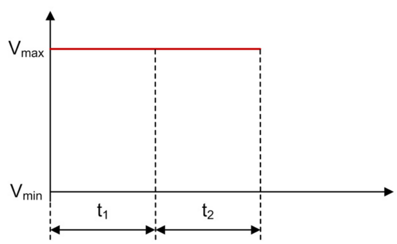


Figure 18.7.1. **Phase-Shifted Full-Bridge - Input Capacitor C_i Voltage Waveform in CCM**

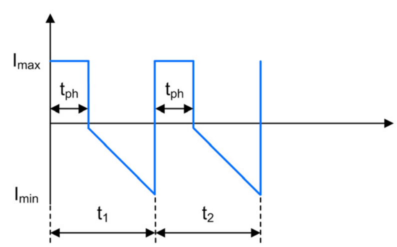


Figure 18.7.2. **Phase-Shifted Full-Bridge - Input Capacitor C_i Current Waveform in CCM**

Min. Input Capacitor Current during t_1: $I_{C_i,min,t_1} = 2 \cdot I_{in,avg} - I_{N_p,max}$

Max. Input Capacitor Current during t_1: $I_{C_i,max,t_1} = 2 \cdot I_{in,avg} - I_{N_p,min}$

Input Capacitor Current during t_2: $I_{C_i,t_2} = 2 \cdot I_{in,avg}$

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

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

18.8. Output Capacitor C_o

18.8.1. CCM.

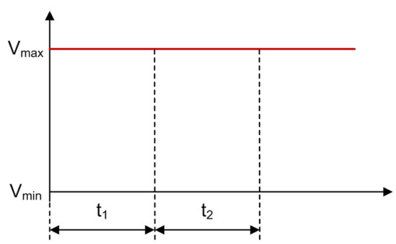


Figure 18.8.1. **Phase-Shifted Full-Bridge - Output Capacitor C_o Voltage Waveform in CCM**

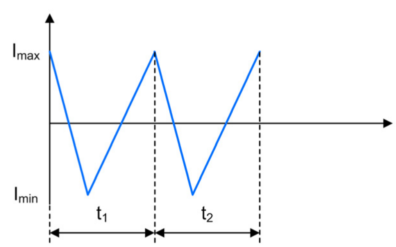


Figure 18.8.2. **Phase-Shifted Full-Bridge - Output Capacitor C_o Current Waveform in CCM**

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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