OPTIREG™ switcher TLS412xD0EPVxx operating modes

About this document

Scope and purpose

The scope of this Application Note is limited to the OPTIREG™ Switcher TLS412x family of synchronous buck DC/DC converters. The purpose is to provide a description of the four operating modes of the TLS412x converter – Pulse Width Modulation Continuous Conduction, Pulse Width Modulation Discontinuous Conduction, Pulse Frequency Modulation Continuous Conduction and Pulse Frequency Modulation Discontinuous Conduction.

Intended audience

This Application Note is intended for users of Infineon's TLS412x family of synchronous buck DC/DC converters.

Table of contents

Table of contents

1 Parameter definitions

$V_{vs} =$ Input voltage

$V_{cc} =$ Output voltage

$I_{cc} =$ Output current

$f_{osc} =$ TLS412x clocked (fixed) switching frequency in PWM mode

$f_{pfm} =$ Variable switching frequency in PFM mode

$L_{out} =$ Output inductance

$C_{out} =$ Output capacitance

$V_d =$ Synchronous rectifier (SW2) diode voltage

$\Delta I_L =$ Output inductor ripple current

$I_L = I_{cc} + \Delta I_L$ Output inductor current

$t_{on,min} =$ High side power switch (SW1) minimum ON time

$T = {}^{1}/_{f_{osc}}$ Switching period in PWM

$D1 = {}^{t1}/_{T}$ ON time duty cycle of the high side switch (SW1)

$D2 = {}^{t2}/_{T}$ OFF time duty cycle of the synchronous rectifier (SW2)

$D3 = {}^{t3}/_{T} = 1 - (D1 + D2)$ Dead time duty cycle (zero inductor current)

2 TLS412x synchronous buck converter

The TLS412x is a synchronous buck converter. A simplified schematic of a synchronous buck converter is shown in Figure 1. The power switches (SW1 & SW2) are integrated into the TLS412x. The high side switch (SW1) is p-channel MOSFET and low side synchronous rectifier (SW2) is an n-channel MOSFET. The output filter ($\mathrm{L_{out}}$ and $\mathrm{C_{out}}$) and load are external to the device.

The TLS412x is available in multiple variants with six different part numbers as shown in Table 1. In this Application Note, the “x” in the part number indicates that the device is available in two current ratings (2A and 2.5A). The TLS4120 is the 2A part and the TLS4125 is the 2.5A part. There are three output voltage variants – 3.3V, 5V and adjustable. Each output voltage variant has its own part number. The TLS412x can operate in low frequency switching (typical 440 kHz) or high frequency switching (typical 2.2MHz). Unless specified otherwise, this Application Note applies to all current, voltage and switching frequency variants.

Table 1 TLS412x Part Numbers

Part Number	Output Current	Output Voltage
TLS4120D0EPV33	2 A	3.3 V
TLS4120D0EPV50	2 A	5 V
TLS4120D0EPV	2 A	Adjustable
TLS4125D0EPV33	2.5 A	3.3 V
TLS4125D0EPV50	2.5 A	5 V
TLS4125D0EPV	2.5 A	Adjustable

The TLS412x operates in continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The TLS412x has two different modulation methods – pulse width modulation (PWM) and pulse frequency modulation (PFM). The four TLS412x operating modes are PWM CCM, PWM DCM, PFM CCM and PFM DCM. The purpose of this Application Note is to describe these operating modes.

The TLS412x incorporates both peak current mode control (CMC) and voltage mode control (VMC). The control method used depends on the operating mode. CMC is used in PWM CCM and PWM DCM while VMC is used in PFM CCM and PFM DCM. The TLS412x automatically applies the correct control method for the given operating mode. A discussion of CMC and VMC is beyond the scope of this Application Note.

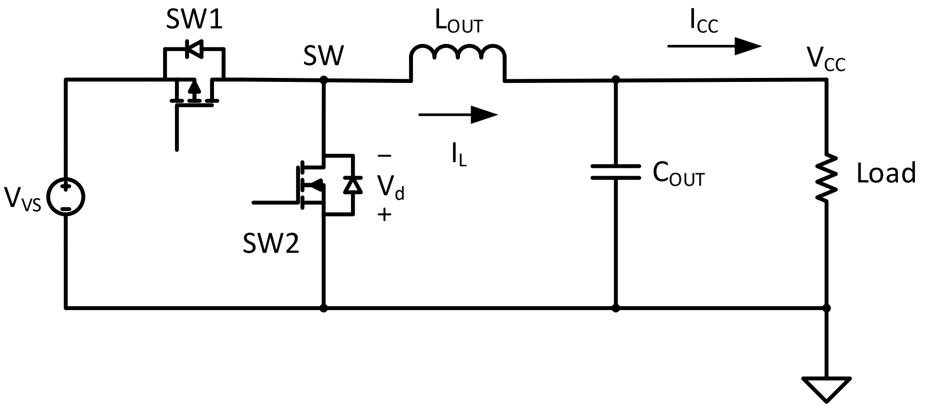

Figure 1 Synchronous Buck Converter

3 Conduction modes

The conduction mode is a description of the current in the output inductor (L_{out}). There are two conduction modes – continuous and discontinuous.

3.1 Continuous conduction mode

In Continuous Conduction Mode (CCM), current is flowing through the inductor during the entire switching period. The inductor current is usually always positive, but can be negative. However, it cannot remain at zero for any portion of the switching period. CCM generally occurs at heavier loads where the synchronous rectifier (SW2) is enabled. Figure 2 shows the CCM inductor current.

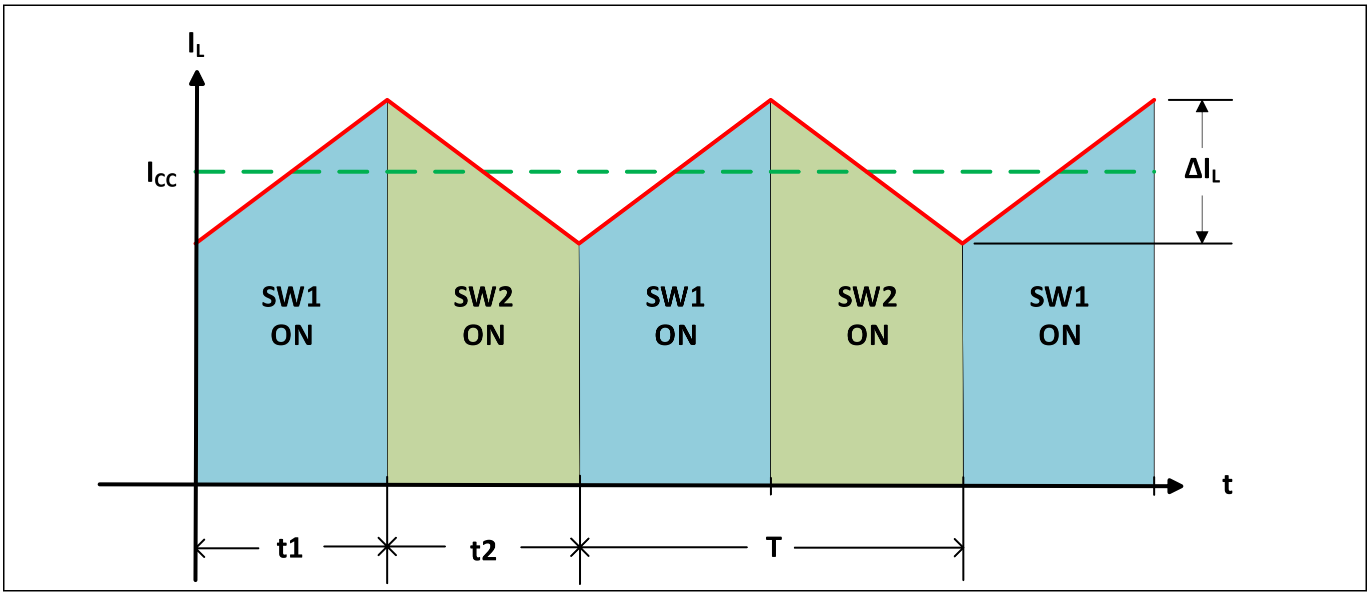

Figure 2 CCM Inductor Current

Forced CCM is an operating mode where the inductor current remains continuous even at light loads. This is accomplished by allowing the inductor current to go negative. This negative current occurs by forcing the synchronous rectifier (SW2) ON throughout the entire OFF time (t2). The TLS412x does not allow forced CCM mode because the synchronous rectifier is disabled prior to the current going negative. The body drain diode then blocks negative current flow. By not allowing forced CCM, the TLS412x will instead operate in DCM (see paragraph 3.2) at light loads. Figure 3 shows the forced CCM inductor current.

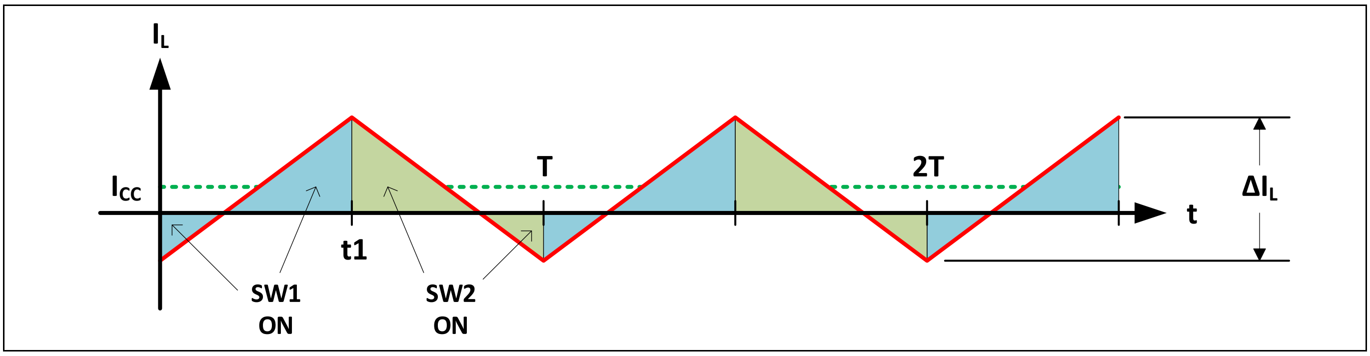

Figure 3 Forced CCM Inductor Current

3.2 Discontinuous conduction mode

In Discontinuous Conduction Mode (DCM), the inductor current is zero (but not negative) for a portion of the switching period.

At lighter loads, the TLS412x disables the synchronous rectifier preventing forced CCM mode. The body drain diode is conducting during the t2 interval (positive inductor current) and reversed biased during the t3 dead time interval (zero inductor current). Figure 4 shows the DCM inductor current.

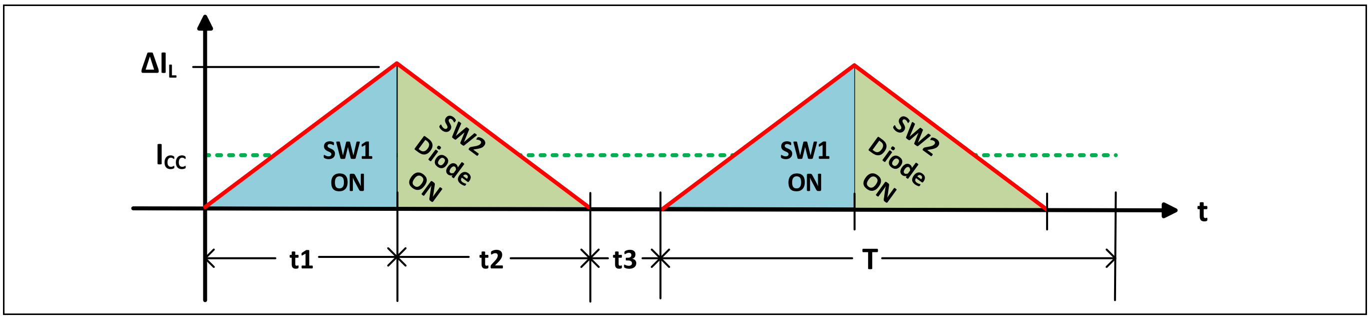

Figure 4 **DCM Inductor Current**

3.3 CCM – DCM boundary

The CCM - DCM boundary is the point at which the inductor current reaches zero exactly at the end of the switching period. At this boundary point the dead time (t3) is zero. Figure 5 shows the inductor current at the CCM – DCM boundary.

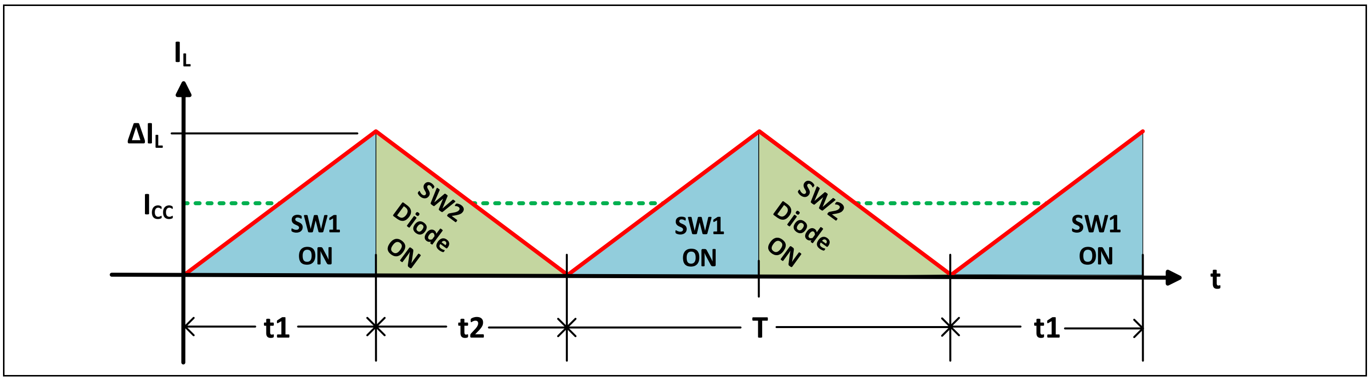

Figure 5 **CCM – DCM Boundary Buck Inductor Current**

4 Modulation methods

In switching converters, there are two basic types of modulation used to regulate the output voltage – pulse width modulation (PWM) and pulse frequency modulation (PFM). The TLS412x operates in both PWM and PFM modes, and handles the transition between these modes automatically.

4.1 Pulse width modulation

Pulse width modulation (PWM) is a method to control the ON time duty cycle (D1) of the high side power switch (SW1) using a fixed switching frequency (f_{osc}). The ON time (t1) is adjusted to regulate the output voltage (V_{cc}). Because the switching frequency is constant, the sum of the SW1 ON and OFF time (t2 + t3) is equal to the switching period T. PWM operation is possible in both CCM and DCM conduction.

The TLS412x uses trailing edge modulation of the t1 ON time. The high side switch (SW1) turn on is initiated by the internal clock oscillator. Turn off (trailing edge) is determined by control loop error signal. A PWM comparator is used to generate the ON time duty cycle. The method by which this is accomplished is different in current mode and voltage mode control. A brief overview of each is provided below. However, a detailed discussion of control methods is beyond the scope of this Application Note.

4.1.1 Voltage mode PWM

A simplified voltage mode controlled buck converter is shown in Figure 6. Figure 7 shows the inputs to the PWM comparator and the resulting ON time duty cycle using trailing edge modulation. V_{ramp} is generated directly from the internal clock oscillator. V_{error} is the output of the control loop error amplifier. The error signal amplitude will change as needed to keep the output voltage in regulation.

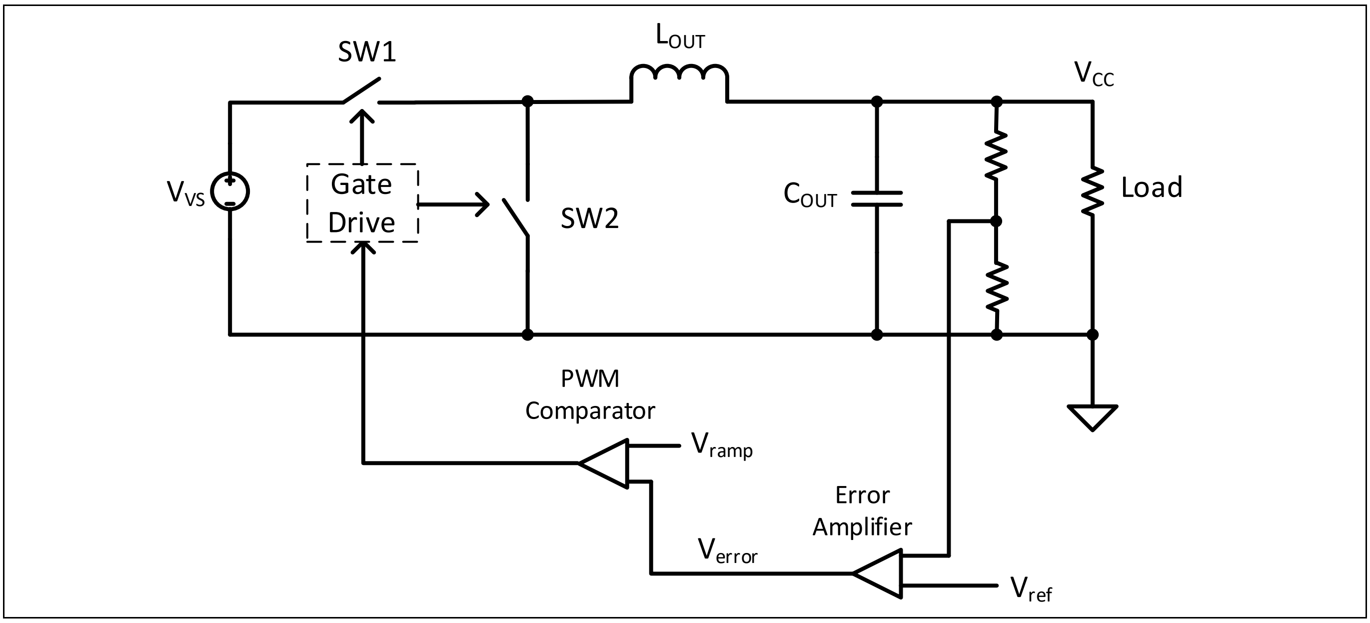

Figure 6 **Simplified Voltage Mode Buck Converter**

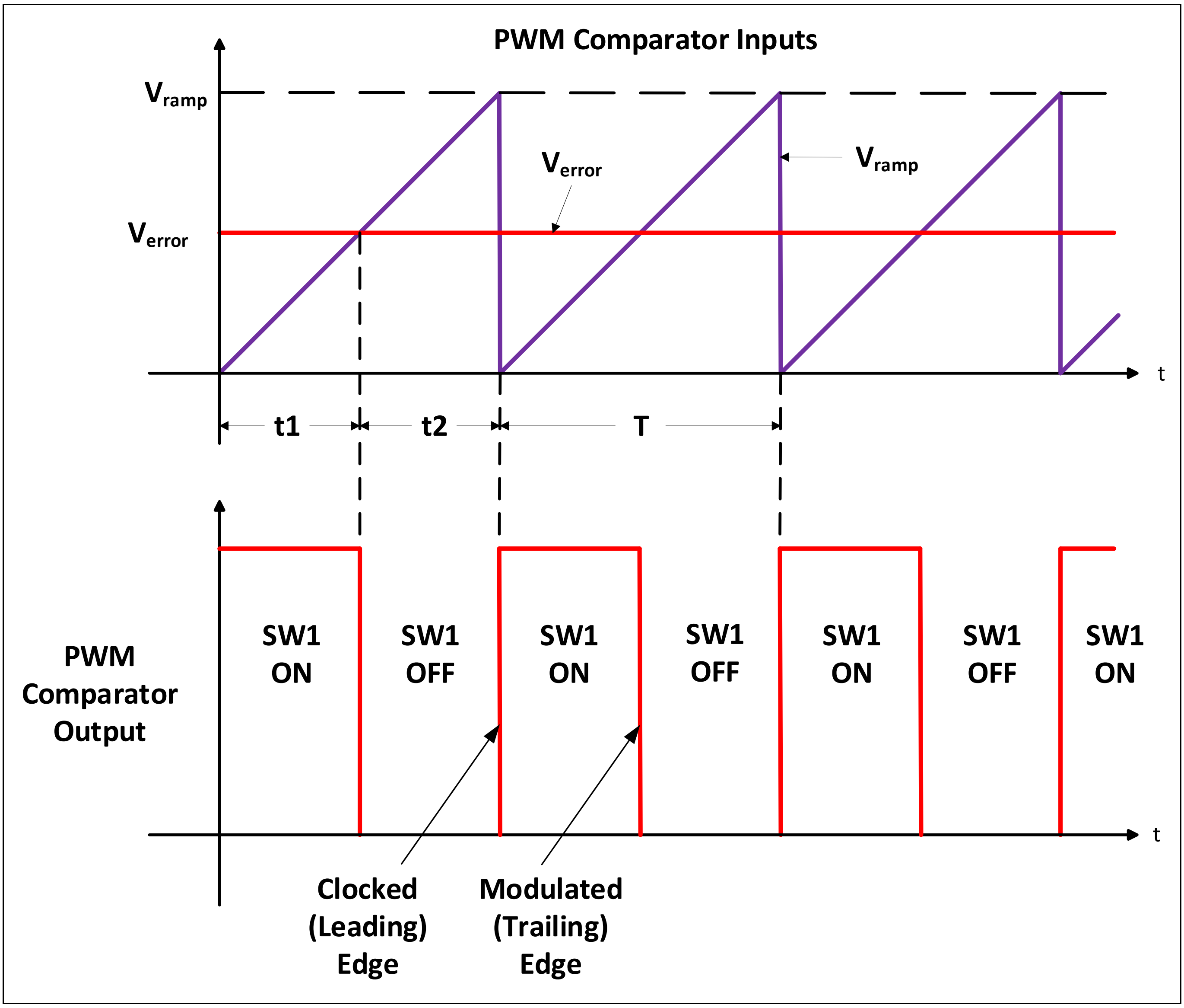

Figure 7 Voltage Mode PWM Comparator

4.1.2 Current mode control PWM

A simplified peak current mode controlled buck converter is shown in Figure 8. Figure 9 shows the inputs to the PWM comparator and the resulting ON time duty cycle using trailing edge modulation. V_{error} is the output of the control loop error amplifier. The error signal will change as needed to keep the output voltage in regulation. Instead of a ramp signal directly from the clock oscillator, a scaled representation of the SW1 current is used. The frequency of this current ramp signal is equal to the internal clock oscillator (SW1 turn on synchronized to the internal clock).

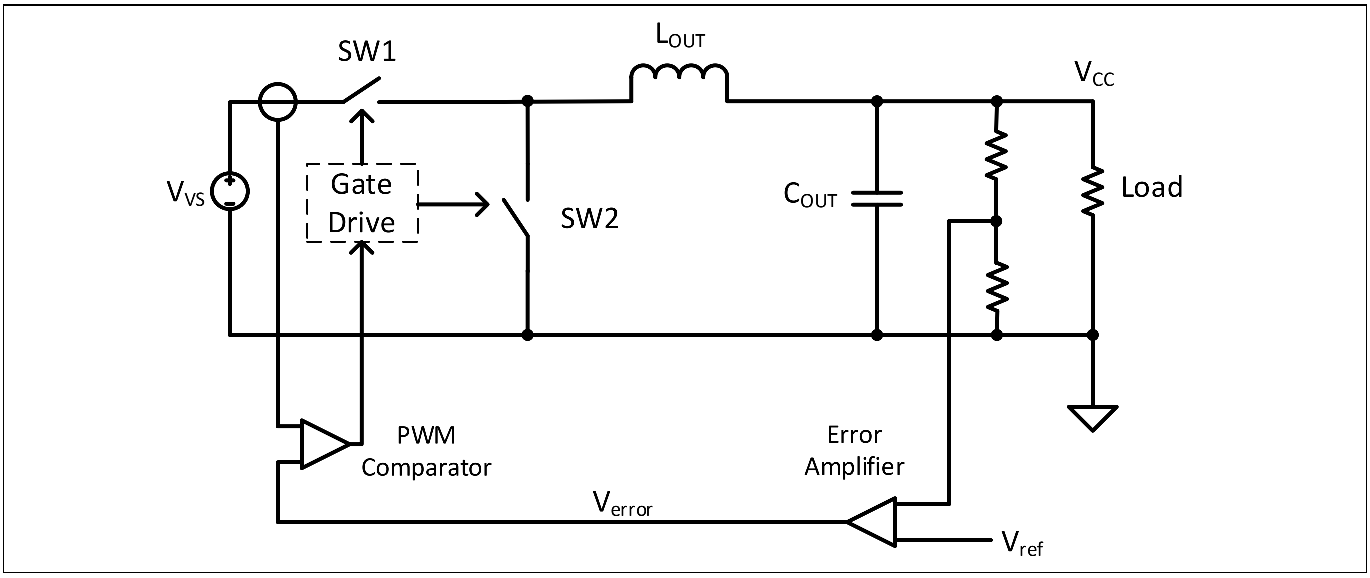

Figure 8 Simplified Peak Current Mode Buck Converter

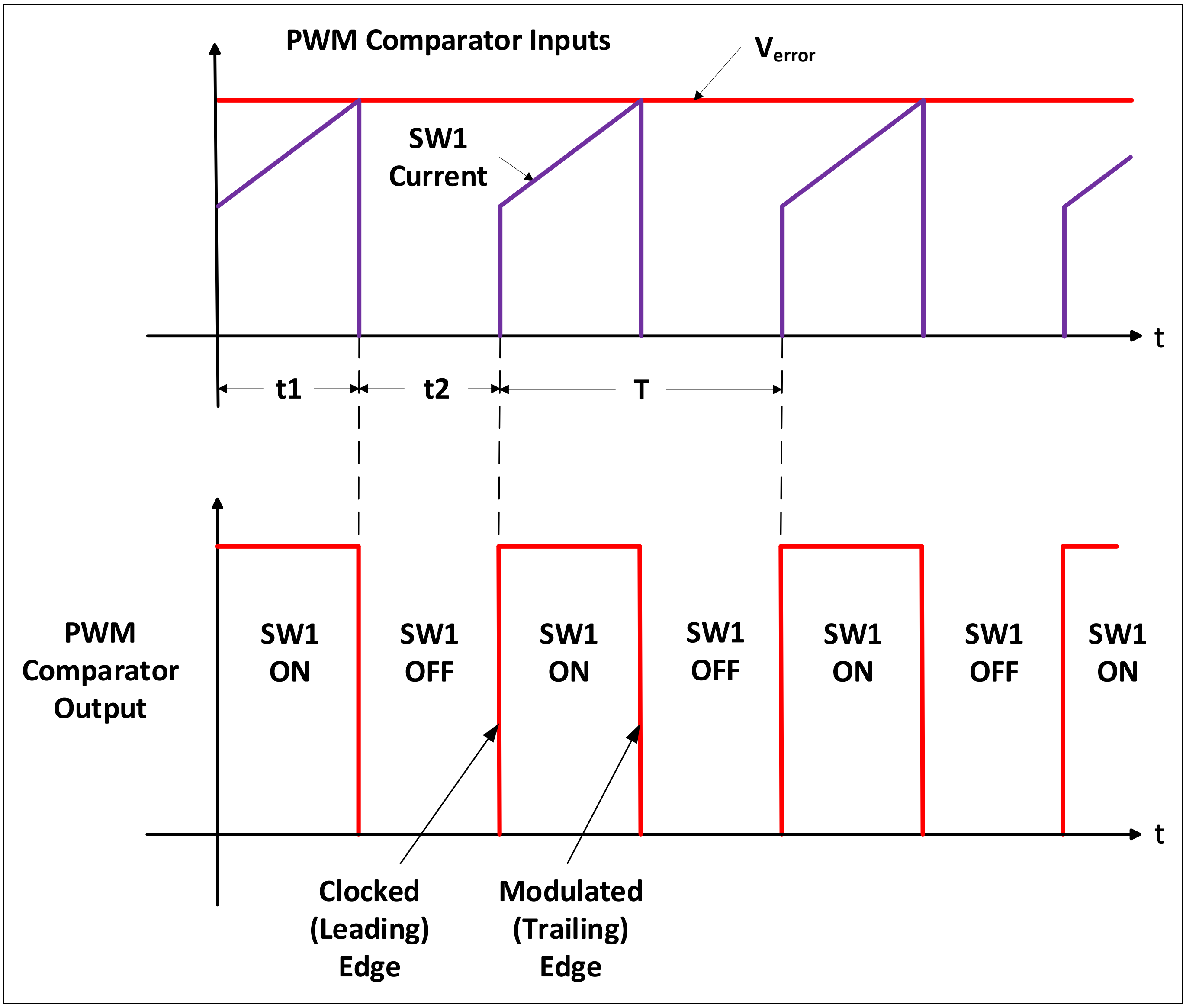

Figure 9 Current Mode PWM Comparator

4.2 Pulse frequency modulation

PFM mode is required when the PWM ON time needed to regulate the output voltage is less the TLS412x minimum on time ($t_{on,min}$) specification. The PFM mode switching frequency is variable, load and input voltage dependent, and always less than the constant PWM mode switching frequency (f_{osc}). The TLS412x provides an efficiency improvement in PFM mode due to the reduced switching frequency.

PFM operation is possible in both CCM and DCM conduction, but must use voltage mode control, as current mode control is not possible.

There are two types of PFM control, constant ON time and current limiting. The TLS412x incorporates constant ON time PFM control. Current limiting PFM control will not be discussed in this Application Note.

4.2.1 Constant ON time PFM

In constant ON time PFM, the high side power switch (SW1) switch ON time is fixed at $t_{on,min}$. The switching frequency (f_{pfm}) is modulated to keep the output in regulation. Like PWM, a control loop error amplifier generates an error signal for regulation. This error signal is used to modulate the switching frequency.

The switching frequency (f_{pfm}) varies with load current and input voltage. The switching frequency decreases with decreasing load (constant input voltage) and increasing input voltage (constant load). This is the result of the control loop increasing the t3 dead time while the ON time is fixed at $t_{on,min}$.

The peak inductor current is dependent on the inductance. Increasing the inductance and/or decreasing input voltage causes the peak current to decrease. Decreasing the inductance and/or increasing the input voltage causes the peak current to increase.

Increasing the inductance causes the output ripple voltage to decrease. Decreasing the inductance causes the output ripple voltage to increase.

Figure 10 shows the effect of increased loading on the inductor current when the input voltage and inductance are held constant. Notice that the inductor ripple current, the ON time, and the OFF time (t2) do not change as the load is increased ($I_{CC3} > I_{CC2} > I_{CC1}$). However, the switching frequency increases ($T_3 < T_2 < T_1$). As the load continues to increase, the dead time (t3) decreases until it reaches zero and converter moves into PFM CCM operation, as shown in graph with I_{CC3}. For this scenario, it is assumed that the input voltage is high enough to prevent PWM operation.

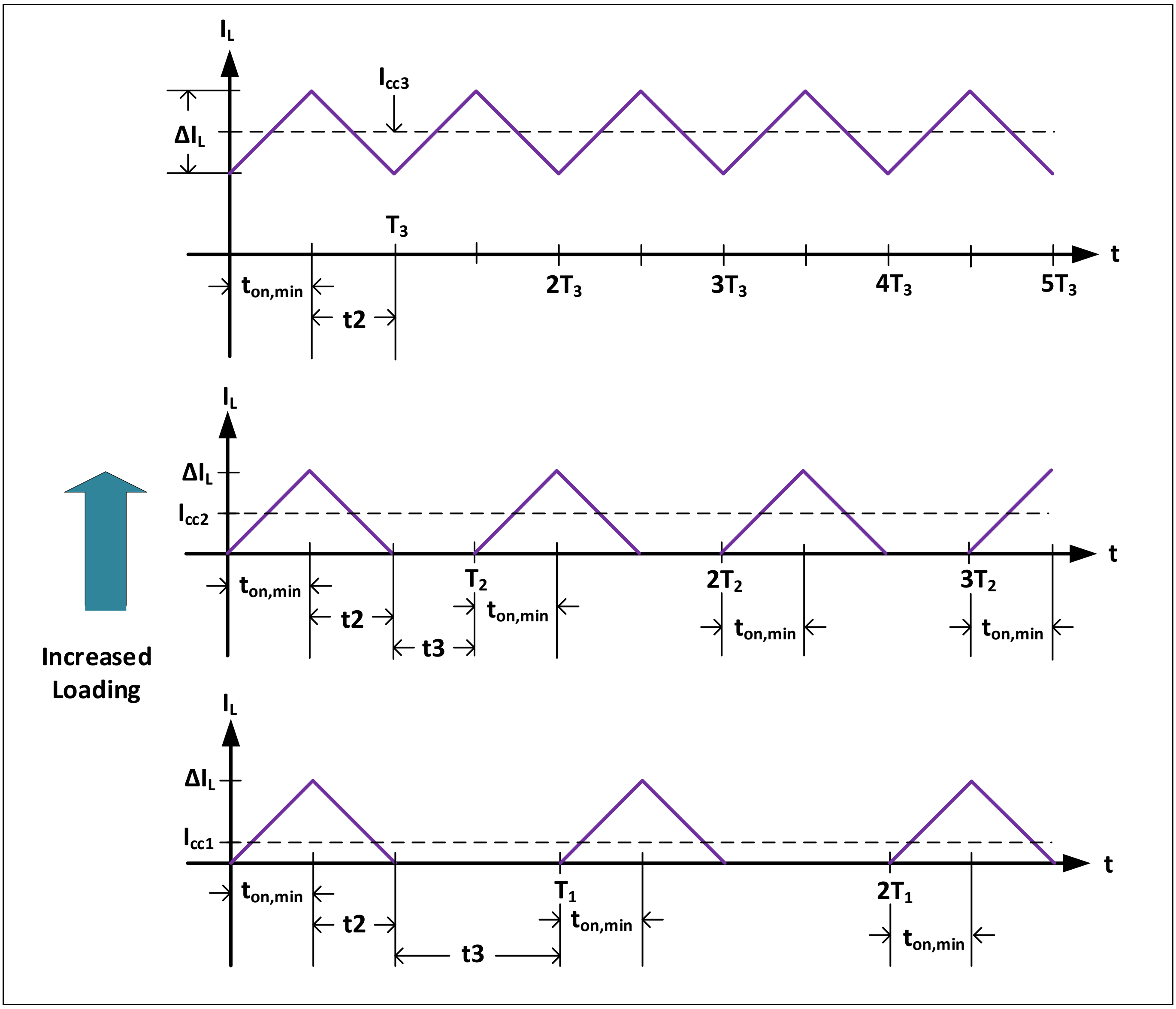

Figure 10 Constant ON Time PFM

5 Boundary definitions

5.1 DCM – CCM boundary conflict

- The General Case:
  The PWM CCM – PWM DCM and PFM CCM – PFM DCM boundaries both separate a DCM region from a CCM region. The synchronous rectifier is enabled in CCM where the body drain diode does not conduct during the OFF time. In DCM, generally the synchronous rectifier is disabled and the body drain diode conducts during the OFF time. Obviously, we cannot have both be true and must select one. In this analysis, it is assumed that the synchronous rectifier is disabled at a DCM – CCM boundary. Because the CCM requirement is not satisfied (diode not conducting), this will result in discontinuities between adjacent boundaries. This mathematical conflict can be eliminated by making the diode voltage zero as shown in paragraph 8.

- TLS412x Operation:
  The TLS412x manages DCM operation somewhat differently than the description of the general case above. The synchronous rectifier is only disabled at very light loads to reduce losses and improve efficiency. Otherwise, the synchronous rectifier remains enabled, but is turned off prior the inductor current going negative. Therefore, the boundary conflict is eliminated as synchronous rectifier is enabled at all the boundaries. The mathematical equations in this Application Note describe the general case where the body drain diode conducts in DCM and at the DCM – CCM boundaries. The equations can easily be modified to describe TLS412x operation by simply setting V_d equal to zero.

5.2 PWM CCM – PWM DCM boundary

The PWM CCM – PWM DCM boundary requirements and assumptions:

- The switching frequency (f_{osc}) is constant during PWM operation.
- The synchronous rectifier is disabled as described in paragraph 5.1. During the OFF time (t2), the body drain diode is conducting the inductor current. For TLS412x applications, set V_d equal to zero.
- The inductor current is similar to that shown in Figure 5.

The duty cycle (D1 & D2) at the boundary:

$$D1 = \frac{V_{cc} + V_d}{V_{vs} + V_d}$$

$$D2 = \frac{D1 \cdot (V_{vs} - V_{cc})}{V_d + V_{cc}} = 1 - D1$$

The inductor ripple current (ΔI_L):

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}}$$

Note that the inductor ripple current is a function of the input voltage.

The minimum load (I_{cc}) at the boundary:

Boundary definitions

$$I_{cc} = \frac{\Delta I_L}{2} = \frac{(V_{vs} - V_{cc}) \cdot D1}{2 \cdot L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{2 \cdot L_{out} \cdot f_{osc}}$$

For a given input voltage, as the load decreases below I_{cc}, the converter moves into DCM and as the load increases above I_{cc}, the converter moves into CCM. Note that the minimum load at this boundary is a function of the input voltage.

Solving for V_{vs} provides an equation describing the input voltage at the boundary:

$$V_{vs} = \frac{V_{cc} \cdot (V_{cc} + V_d) + 2 \cdot I_{cc} \cdot L_{out} \cdot V_d \cdot f_{osc}}{V_d + V_{cc} - 2 \cdot I_{cc} \cdot L_{out} \cdot f_{osc}}$$

The maximum input voltage at the PWM CCM – PWM DCM boundary occurs when the high side switch (SW1) ON time is equal to the TLS412x specified minimum ON time ($t_{on,min}$).

$$D1 = t_{on,min} \cdot f_{osc} = \frac{V_{cc} + V_d}{V_{vs\_max} + V_d}$$

Solving for V_{vs_max}, the maximum input voltage at the boundary is:

$$V_{vs\_max} = \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d$$

The minimum input voltage (V_{vs_min}) at the boundary is limited by the maximum available duty cycle. For the TLS412x, the maximum duty cycle is 100%. In addition, the TLS412x has a minimum input specification of 3.7 volt ($V_{vs,dec}$).

$$V_{vs\_min} = V_{vs,dec} = 3.7 \cdot \text{volt}$$

The minimum and maximum loads (I_{cc_min} and I_{cc_max}) and inductor ripple currents (ΔI_{L_min} and ΔI_{L_max}) are:

$$I_{cc\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot V_{cc}}{2 \cdot L_{out} \cdot f_{osc} \cdot V_{vs\_min}} = \frac{\Delta I_{L\_min}}{2}$$

$$I_{cc\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot V_{cc}}{2 \cdot L_{out} \cdot f_{osc} \cdot V_{vs\_max}} = \frac{\Delta I_{L\_max}}{2}$$

$$\Delta I_{L\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot V_{cc}}{L_{out} \cdot f_{osc} \cdot V_{vs\_min}}$$

$$\Delta I_{L\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot V_{cc}}{L_{out} \cdot f_{osc} \cdot V_{vs\_max}}$$

5.3 PWM DCM – PFM DCM boundary

The PWM DCM – PFM DCM boundary requirements and assumptions:

- At a PWM - PFM mode boundary, the switching frequency (f_{osc}) is constant with t1 = $t_{on,min}$.
- The synchronous rectifier is disabled during DCM operation. During the OFF time (t2), the body drain diode is conducting the inductor current. For TLS412x applications, set V_d equal to zero.

Boundary definitions

- The inductor current is similar to that shown in Figure 4.

The duty cycle (D1, D2 & D3) at the boundary:

$$D1 = t_{on,min} \cdot f_{osc}$$

$$D2 = \frac{t_{on,min} \cdot f_{osc} \cdot (V_{vs} - V_{cc})}{V_d + V_{cc}}$$

$$D3 = 1 - (D1 + D2)$$

The output voltage (V_{cc}) is a function of D1 and D2:

$$V_{cc} = \frac{D1 \cdot V_{vs} - D2 \cdot V_d}{D1 + D2}$$

The inductor ripple current (ΔI_L):

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}}$$

Note that the inductor ripple current is a function of the input voltage.

The minimum load (I_{cc}) at the boundary is:

$$I_{cc} = \frac{1}{2} \cdot \Delta I_L \cdot (D1 + D2) = \frac{(V_{vs} - V_{cc}) \cdot D1 \cdot (D1 + D2)}{2 \cdot L_{out} \cdot f_{osc}} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{vs} - V_{cc}) \cdot (V_d + V_{vs})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

For a given input voltage, as the load decreases below I_{cc}, the converter moves into PFM DCM and as the load increases above I_{cc}, the converter moves into PWM DCM. Note that the minimum load at this boundary is a function of the input voltage.

Solving for V_{vs} provides an equation describing the input voltage at the boundary:

$$V_{vs} = \frac{V_{cc} - V_d}{2} + \frac{V_d + V_{cc}}{2 \cdot D1} \cdot \sqrt{D1^2 + \frac{8 \cdot I_{cc} \cdot L_{out} \cdot f_{osc}}{V_d + V_{cc}}}$$

As the input voltage increases while on the boundary, the ON time will decrease to the point where it will equal $t_{on,min}$. This is the input voltage where the PWM DCM - PFM DCM and PWM CCM - PWM DCM boundaries will intersect. Therefore, the maximum input voltage on the PWM DCM - PFM DCM boundary should be the same as that defined for the PWM CCM - PWM DCM boundary.

$$V_{vs\_max} = \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d$$

The minimum input voltage (V_{vs_min}) at the boundary is limited by the maximum available duty cycle. For the TLS412x, the maximum duty cycle is 100%. In addition, the TLS412x has a minimum input specification of 3.7 volt ($V_{vs,dec}$).

Boundary definitions

$$V_{vs\_min} = V_{vs,dec} = 3.7 \cdot volt$$

The minimum and maximum loads (I_{cc_min} and I_{cc_max}) and inductor ripple currents (ΔI_{L_min} and ΔI_{L_max}) are:

$$I_{cc\_min} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{rs\_min} - V_{cc}) \cdot (V_d + V_{vs\_min})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

$$I_{cc\_max} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{rs\_max} - V_{cc}) \cdot (V_d + V_{vs\_max})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

$$\Delta I_{L\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot t_{on,min}}{L_{out}}$$

$$\Delta I_{L\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot t_{on,min}}{L_{out}}$$

5.4 PWM CCM – PFM CCM boundary

The PWM CCM – PFM CCM boundary requirements and assumptions:

- The switching frequency (f_{osc}) is constant with t1 = $t_{on,min}$ at the PWM CCM - PFM CCM boundary.
- The synchronous rectifier is enabled during CCM. During the OFF time (t2), the body drain diode is not conducting the inductor current.
- The inductor current is similar to that shown in Figure 2.

The duty cycle (D1 & D2) at the boundary:

$$D1 = t_{on,min} \cdot f_{osc}$$

$$D2 = 1 - D1$$

$$D3 = 0$$

The input voltage at the PWM CCM - PFM CCM boundary is reached when the ON time (t1) equals $t_{on,min}$.

$$t_{on,min} \cdot f_{osc} = \frac{V_{cc}}{V_{vs}}$$

Solving for V_{vs}:

$$V_{vs} = \frac{V_{cc}}{f_{osc} \cdot t_{on,min}}$$

This result is constant across the boundary as all parameters in the equation are constant.

The boundary minimum load (I_{cc_min}) occurs at the boundary between PWM CCM and PWM DCM and is equal to one half of the inductor ripple current.

$$I_{cc\_min} = \frac{(V_{vs} - V_{cc})}{2 \cdot L_{out} \cdot f_{osc}} \cdot \frac{V_{cc}}{V_{vs}} = \frac{(1 - f_{osc} \cdot t_{on,min}) \cdot V_{cc}}{2 \cdot L_{out} \cdot f_{osc}}$$

Boundary definitions

There is no theoretical maximum load at the boundary as the converter is pushed further into CCM as the load is increased. Therefore, the maximum load is (I_{cc_max}) defined by the specified maximum rated current of the TLS412x.

$$I_{cc\_max} = I_{cc\_rated\_max}$$

The inductor ripple current (ΔI_L):

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{V_{cc} \cdot D2}{L_{out} \cdot f_{osc}}$$

Note that the inductor ripple current is constant at the boundary as V_{vs}, V_{cc}, $t_{on,min}$ and L_{out} are all constant.

5.4.1 Effective minimum ON time

The discussion in paragraph 5.4 is based upon the theoretical minimum ON time as specified in the TLS412x datasheet ($t_{on,min}$). However, the actual or effective minimum ON time in an application differs slightly from the theoretical. The effective minimum ON time is somewhat dependent on the output load current (I_{cc}) as it increases with decreasing load. This leads to a decrease in the PWM CCM - PFM CCM input voltage boundary as defined in paragraph 5.4. Figure 11 shows this typical relationship for the TLS4120D0EPV33 at both 440 kHz and 2.2 MHz switching frequencies (f_{osc}).

There is a parasitic capacitance (C_{par}) at the switch node (SW) as shown in Figure 12. This capacitance is a parallel combination of the SW2 output capacitance and the printed circuit board (PCB) capacitance. It is the time needed to discharge this capacitance which accounts for the TLS412x $t_{on,min}$load dependency.

During the SW1 ON time, the switch node parasitic capacitance is charged up to the input voltage (V_{vs}). After the control loop turns off SW1 and before the synchronous rectifier (SW2) is turned on, the output inductor (L_{out}) acts as a current source discharging the switch node capacitance to ground. The average current in the output inductor during CCM is equal to the load current (I_{cc}) as shown in Figure 2. Therefore, the discharge time is determined by the load current and the parasitic capacitance. Reducing the load current and/or increasing the parasitic capacitance will increase the discharge time and the minimum ON time. The discharge time is also slightly depenent on the input voltage. It is more noticable at higher input voltages if the switching frequency (f_{osc}) is something other than the typical (440 kHz or 2.2 MHz).

The effective minimum ON time with respect to the theoretical is shown in Figure 13.

For a theoretical analysis related to the PFM mode, it is reasonable to use typical datasheet minimum ON time ($t_{on,min}$). However, the user should consider the actual behavior in the application taking into account tolerances, output loading and the PCB layout.

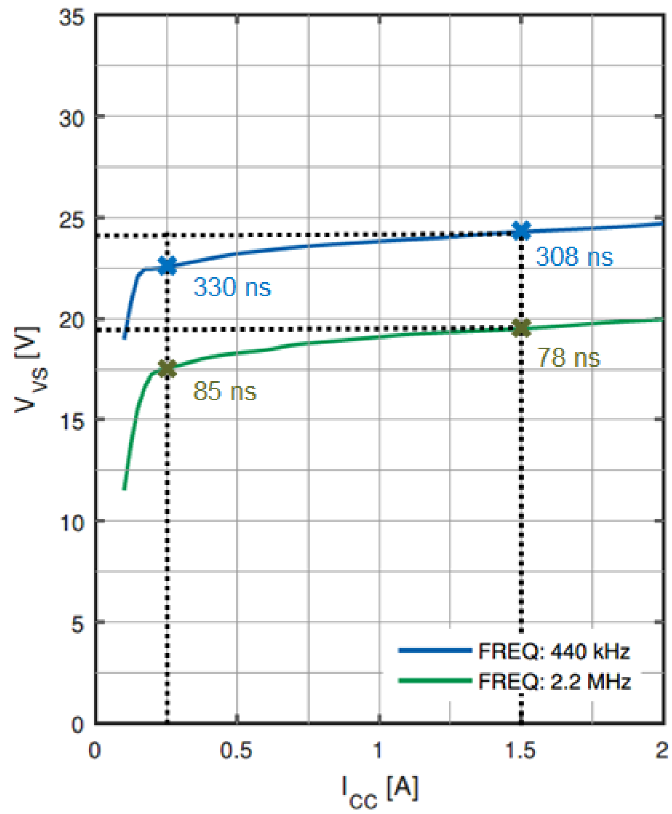

Figure 11 TLS4120D0EPV33 Minimum ON Time at PFM – PWM Boundary

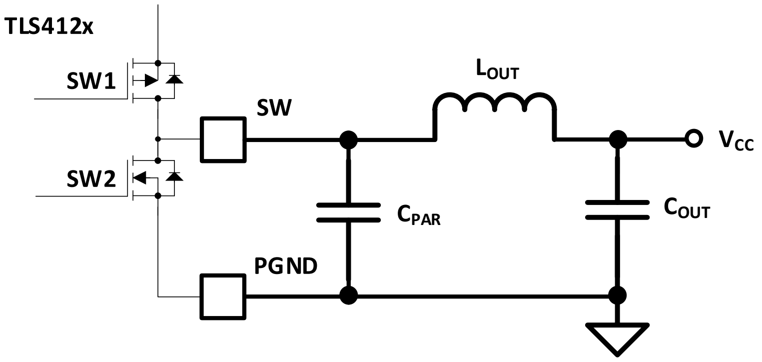

Figure 12 TLS412x Switch Node

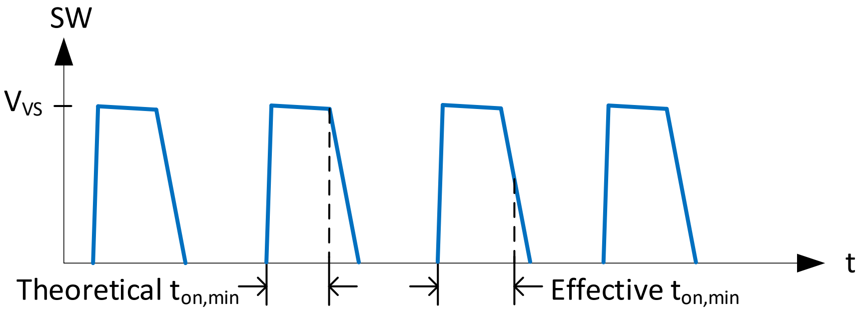

Figure 13 Switch Node Effective Minimum ON Time

5.5 PFM CCM – PFM DCM boundary

The PFM CCM – PFM DCM boundary requirements and assumptions:

- The switching frequency (f_{pfm}) is variable with t1 = $t_{on,min}$ at the PFM DCM - PFM CCM boundary. At the minimum input voltage, the switching frequency is maximum and equal to f_{osc}. As the input voltage is increased, the switching frequency decreases and is minimum at the maximum input voltage.
- The synchronous rectifier is disabled as described in paragraph 5.1. During the OFF time (t2), the body drain diode is conducting the inductor current. For TLS412x applications, set V_d equal to zero.
- The inductor current is similar to that shown in Figure 5.

The minimum input voltage at the boundary where the ON time (t1) = $t_{on,min}$ and the switching frequency is at maximum (f_{osc}):

$$f_{osc} \cdot t_{on,min} = \frac{V_{cc} + V_d}{V_{vs,min} + V_d}$$

Solving for V_{vs_min}:

$$V_{vs\_min} = \frac{V_d + V_{cc}}{f_{osc} \cdot t_{on,min}} - V_d$$

There is no theoretical maximum limit to the input voltage at the boundary. However, it is limited by the TLS412x maximum specified rated input voltage of 42 volt ($V_{vs,dyn}$).

$$V_{vs\_max} = V_{vs,dyn} = 42 \cdot \text{volt}$$

The duty cycle (D1, D2 & D3) at the boundary:

$$D1 = \frac{V_{cc} + V_d}{V_{vs} + V_d}$$

$$D2 = \frac{D1 \cdot (V_{vs} - V_{cc})}{V_d + V_{cc}} = 1 - D1 \quad \text{and} \quad D3 = 0$$

The inductor ripple current (ΔI_L):

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot t_{on\_min}}{L_{out}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{pfm}} = \frac{(V_{vs\_max} - V_{cc}) \cdot D1}{L_{out} \cdot f_{pfm}}$$

Note that the inductor ripple current is a function of the input voltage.

$$\Delta I_{L\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot t_{on\_min}}{L_{out}}$$

$$\Delta I_{L\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot t_{on\_min}}{L_{out}}$$

The load current (I_{cc}) on the boundary is described as the boundary current between CCM and DCM. Note that this current is a function of input voltage.

Boundary definitions

$$I_{cc} = \frac{\Delta I_L}{2} = \frac{(V_{vs} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}}$$

$$I_{cc\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}}$$

$$I_{cc\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}}$$

Knowing ΔI_L, the switching frequency at the boundary (f_{pfm}):

$$f_{pfm} = \frac{D2 \cdot (V_d + V_{cc})}{t_{on,min} \cdot (V_{vs} - V_{cc})} = \frac{V_d + V_{cc}}{t_{on,min} \cdot (V_d + V_{vs})}$$

Note that the switching frequency decreases as the input voltage increases.

$$f_{pfm\_max} = \frac{V_d + V_{cc}}{t_{on,min} \cdot (V_d + V_{vs\_min})} = f_{osc}$$

$$f_{pfm\_min} = \frac{V_d + V_{cc}}{t_{on,min} \cdot (V_d + V_{vs\_max})}$$

Knowing ΔI_L, the input voltage (V_{vs}) at the boundary:

$$V_{vs} = V_{cc} + \frac{2 \cdot I_{cc} \cdot L_{out}}{t_{on,min}}$$

6 Operating regions

6.1 PWM CCM region

The synchronous rectifier is enabled in CCM (body diode is not conducting during the t2 OFF time). For TLS412x applications, set V_d equal to zero (paragraph 5.1).

6.1.1 Criteria for PWM CCM operation

- The input voltage must be less than V_{vs_max} to prevent PFM operation.

$$V_{vs} < V_{vs\_max} = \frac{V_{cc}}{t_{on,min} \cdot f_{osc}}$$

- For a specified input voltage, the load current must be greater than I_{cc_min} to prevent DCM operation.

$$I_{cc} > I_{cc\_min} = \frac{(V_d + V_{cc}) \cdot (V_{vs} - V_{cc})}{2 \cdot L_{out} \cdot f_{osc} \cdot (V_d + V_{vs})}$$

- Decreasing the input voltage while in PFM CCM causes an increase in the ON time (t1). When the ON time needed to maintain PFM operation is greater than $t_{on,min}$, the converter enters PWM CCM operation. As a result, the switching frequency (f_{osc}) is constant and is determined from the TLS412x clock oscillator.

$$t1 > t_{on,min}$$

$$t_{on,min} < \frac{V_{cc}}{V_{vs} \cdot f_{osc}}$$

6.1.2 PWM CCM equations

$$D1 = \frac{V_{cc}}{V_{vs}} = t1 \cdot f_{osc}$$

$$D2 = \frac{D1 \cdot (V_{vs} - V_{cc})}{V_{cc}} = 1 - D1 = t2 \cdot f_{osc}$$

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{V_{cc} \cdot D2}{L_{out} \cdot f_{osc}}$$

6.2 PFM CCM region

The synchronous rectifier is enabled in CCM (body diode is not conducting during the t2 OFF time). For TLS412x applications, set V_d equal to zero (paragraph 5.1).

6.2.1 Criteria for PFM CCM operation

- The input voltage must be greater than V_{vs_min} to prevent PWM operation.

$$V_{vs} > V_{vs\_min} = \frac{V_{cc}}{t_{on,min} \cdot f_{osc}}$$

Operating regions

- For a specified input voltage, the load current (I_{cc}) must be greater than I_{cc_min} to prevent DCM operation.

  $$\text{If } V_{vs} > \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d$$

  $$\text{Then } I_{cc} > I_{cc\_min} = \frac{(V_{vs} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}} = \frac{\Delta I_L}{2}$$

  $$\text{If } \frac{V_{cc}}{t_{on,min} \cdot f_{osc}} < V_{vs} < \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d$$

  $$\text{Then } I_{cc} > I_{cc\_min} > \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{vs} - V_{cc}) \cdot (V_d + V_{vs})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

- Increasing the input voltage while in PWM CCM causes a reduction in the ON time (t1). When the ON time needed to maintain PWM operation is less than $t_{on,min}$, the converter enters PFM CCM operation. As a result, the switching frequency (f_{pfm}) is not constant, less than f_{osc} and a function of the input voltage.

  $$t1 = t_{on,min}$$

  $$f_{osc} > f_{pfm}$$

  $$t_{on,min} > \frac{V_{cc}}{V_{vs} \cdot f_{osc}}$$

6.2.2 PFM CCM equations

$$f_{pfm} = \frac{V_{cc}}{V_{vs} \cdot t_{on,min}}$$

$$D1 = \frac{V_{cc}}{V_{vs}} = t1 \cdot f_{pfm} = t_{on,min} \cdot f_{pfm}$$

$$D2 = \frac{D1 \cdot (V_{vs} - V_{cc})}{V_{cc}} = 1 - D1 = t2 \cdot f_{pfm}$$

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{pfm}} = \frac{t_{on,min} \cdot (V_{vs} - V_{cc})}{L_{out}} = \frac{V_{cc} \cdot D2}{L_{out} \cdot f_{pfm}}$$

6.3 PFM DCM region

The synchronous rectifier is disabled in DCM (body diode is conducting during the t2 OFF time). For TLS412x applications, set V_d equal to zero (paragraph 5.1).

6.3.1 Criteria for PFM DCM operation

- The t1 ON time is equal to $t_{on,min}$ during PFM mode operation. As a result, the switching frequency (f_{pfm}) is not constant, is less than f_{osc} and is a function of the input voltage. DCM operation also causes a load dependency on the switching frequency.

  $$t1 = t_{on,min}$$

$$f_{osc} > f_{pfm}$$

- For a specified input voltage, the load current must be less than I_{cc_max} to prevent PWM DCM or PFM CCM operation.

$$\text{If } V_{vs} > \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d$$

$$\text{Then } I_{cc\_max} = \frac{\Delta I_L}{2}$$

$$\text{If } V_{vs} < \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d$$

$$\text{Then } I_{cc\_max} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{vs} - V_{cc}) \cdot (V_d + V_{vs})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

- In DCM, the D3 duty cycle is greater than zero.

6.3.2 PFM DCM equations

$$f_{pfm} = \frac{2 \cdot L_{out} \cdot I_{cc} \cdot (V_{cc} + V_d)}{t_{on,min}^2 \cdot (V_{vs} + V_d) \cdot (V_{vs} - V_{cc})}$$

$$D1 = t1 \cdot f_{pfm} = t_{on,min} \cdot f_{pfm}$$

$$D2 = t2 \cdot f_{pfm} = \frac{f_{pfm} \cdot t_{on,min} \cdot (V_{vs} - V_{cc})}{V_d + V_{cc}}$$

$$D3 = t3 \cdot f_{pfm} = 1 - (D1 + D2)$$

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot t_{on,min}}{L_{out}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{pfm}}$$

$$I_{cc} = \frac{1}{2} \cdot \Delta I_L \cdot (D1 + D2) = \frac{1}{2} \cdot \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{pfm}} \cdot (D1 + D2) = \frac{f_{pfm} \cdot t_{on,min}^2 \cdot (V_{vs} - V_{cc}) \cdot (V_d + V_{vs})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

$$V_{cc} = \frac{D1 \cdot V_{vs} - D2 \cdot V_d}{D1 + D2}$$

6.4 PWM DCM region

The synchronous rectifier is disabled in DCM (body diode is conducting during the t2 OFF time). For TLS412x applications, set V_d equal to zero (paragraph 5.1).

6.4.1 Criteria for PWM DCM operation

- The t1 ON time is greater than $t_{on,min}$ and the switching frequency (f_{osc}) is constant (determined from the TLS412x clock oscillator) during PWM operation.
- In DCM, the D3 duty cycle is greater than zero.

Operating regions

- For a specified input voltage, the load current must be less than I_{cc_max} in order to avoid PWM CCM operation.

  $$I_{cc} < I_{cc\_max} = \frac{(V_d + V_{cc}) \cdot (V_{vs} - V_{cc})}{2 \cdot L_{out} \cdot f_{osc} \cdot (V_d + V_{vs})}$$

- For a specified input voltage, the load current must be greater than I_{cc_min} in order to avoid PFM DCM operation.

  $$I_{cc} > I_{cc\_min} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{vs} - V_{cc}) \cdot (V_d + V_{vs})}{2 \cdot L_{out} \cdot (V_d + V_{cc})}$$

- The input voltage must be less than V_{vs_max} in order to avoid PFM mode operation.

  $$V_{vs} < V_{vs\_max} = \frac{V_d + V_{cc}}{f_{osc} \cdot t_{on,min}} - V_d$$

6.4.2 PWM DCM equations

$$D1 = t1 \cdot f_{osc} = \frac{I_{cc} \cdot \sqrt{\frac{2 \cdot L_{out} \cdot f_{osc} \cdot (V_{vs} - V_{cc}) \cdot (V_d + V_{cc}) \cdot (V_d + V_{vs})}{I_{cc}}}}{(V_{vs} - V_{cc}) \cdot (V_d + V_{vs})}$$

$$D2 = t2 \cdot f_{osc} = \frac{D1 \cdot (V_{vs} - V_{cc})}{V_d + V_{cc}}$$

$$D3 = t3 \cdot f_{osc} = 1 - (D1 + D2)$$

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}}$$

$$V_{cc} = \frac{D1 \cdot V_{vs} - D2 \cdot V_d}{D1 + D2}$$

$$I_{cc} = \frac{(V_{vs} - V_{cc}) \cdot D1}{2 \cdot L_{out} \cdot f_{osc}} \cdot (D1 + D2)$$

7 Transition from PFM DCM to PWM CCM

Figure 14 shows the output inductor current during the transition from PFM DCM at light loading to PWM CCM at heavy loading.

As the load increases from light to heavy, the operating mode transitions from PFM DCM → PWM DCM → PWM CCM. As the load decreases from heavy to light, the operating mode transitions from PWM CCM → PWM DCM → PFM DCM.

For this scenario, it is assumed that the input voltage is low enough (less than $\frac{V_{cc}}{f_{osc} \cdot t_{on,min}}$) to prevent PFM CCM operation.

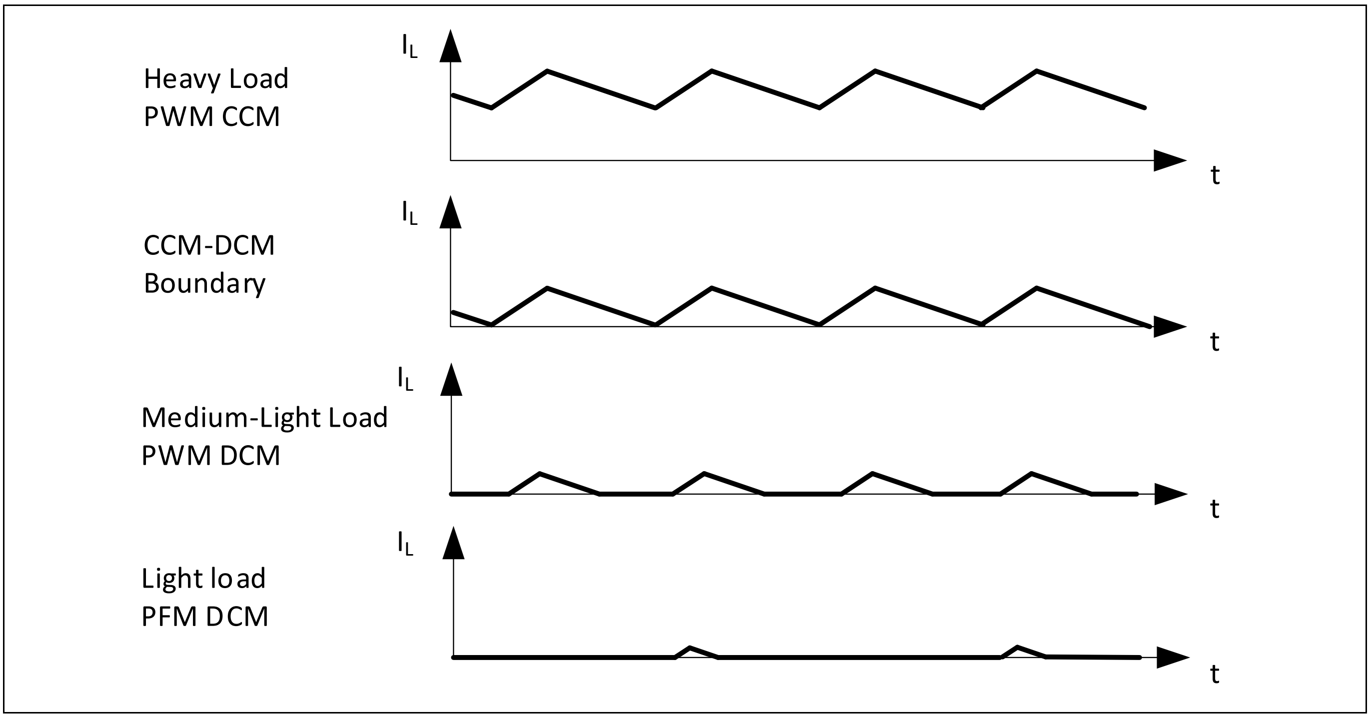

Figure 14 Inductor Current Transition PFM DCM ↔ PWM CCM

8 Example

$V_{vs,dec} = 3.7 \cdot \mathrm{volt}$	TLS412x minimum operating voltage
$V_{vs,dyn} = 42 \cdot \mathrm{volt}$	TLS412x maximum operating voltage
$V_{cc} = 3.3 \cdot \mathrm{volt}$	Output voltage
$f_{osc} = 2.2 \cdot \mathrm{MHz}$	TLS412x oscillator frequency
$L_{out} = 2.2 \cdot \mu\mathrm{H}$	Output inductance
$t_{on,min} = 78 \cdot \mathrm{ns}$	Typical TLS412x minimum ON time (high frequency mode)
$V_d = 0 \cdot \mathrm{volt}$	TLS412x synchronous rectifier body drain diode voltage

The results shown in this example are for a typical situation using nominal parameter values. Component tolerances have not been considered.

As discussed in paragraph 5.1, the synchronous rectifier body drain diode voltage is zero volts in TLS412x applications.

8.1 PWM CCM – PWM DCM boundary

At the boundary, the input voltage as a function of load current is described below and in Figure 15.

$$V_{vs}(I_{cc}) = \frac{V_{cc} \cdot (V_{cc} + V_d) + 2 \cdot I_{cc} \cdot L_{out} \cdot V_d \cdot f_{osc}}{V_d + V_{cc} - 2 \cdot I_{cc} \cdot L_{out} \cdot f_{osc}}$$

With $V_{vs} = V_{vs\_min}$:

$$V_{vs\_min} = V_{vs,dec} = 3.7 \cdot \mathrm{volt}$$

$$D1 = \frac{V_{cc} + V_d}{V_{vs\_min} + V_d} = 89.19 \cdot \%$$

$$D2 = \frac{D1 \cdot \left(V_{vs\_min} - V_{cc}\right)}{V_d + V_{cc}} = 10.81 \cdot \%$$

$$D1 + D2 = 100 \cdot \%$$

$$\Delta I_{L\_min} = \frac{\left(V_{vs\_min} - V_{cc}\right) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}} = 73.71 \cdot \mathrm{mA}$$

$$I_{cc\_min} = \frac{(V_{cc} + V_d) \cdot D2}{2 \cdot L_{out} \cdot f_{osc}} = \frac{\left(V_{vs\_min} - V_{cc}\right) \cdot D1}{2 \cdot L_{out} \cdot f_{osc}} = \frac{\Delta I_{L\_min}}{2} = 36.86 \cdot \mathrm{mA}$$

With $V_{vs} = V_{vs\_max}$:

$$V_{vs\_max} = \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d = 19.23 \cdot \mathrm{volt}$$

Example

$$D1 = \frac{V_{cc} + V_d}{V_{vs\_max} + V_d} == 17.16 \cdot \%$$

$$D2 = \frac{D1 \cdot \left(V_{vs\_max} - V_{cc}\right)}{V_d + V_{cc}} = 82.84 \cdot \%$$

$$D1 + D2 = 100 \cdot \%$$

$$\Delta I_{L\_max} = \frac{\left(V_{vs\_max} - V_{cc}\right) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{\left(V_{cc} + V_d\right) \cdot D2}{L_{out} \cdot f_{osc}} = 564.82 \cdot mA$$

$$I_{cc\_max} = \frac{\left(V_{cc} + V_d\right) \cdot D2}{2 \cdot L_{out} \cdot f_{osc}} = \frac{\left(V_{vs\_max} - V_{cc}\right) \cdot D1}{2 \cdot L_{out} \cdot f_{osc}} = \frac{\Delta I_{L\_max}}{2} = 282.41 \cdot mA$$

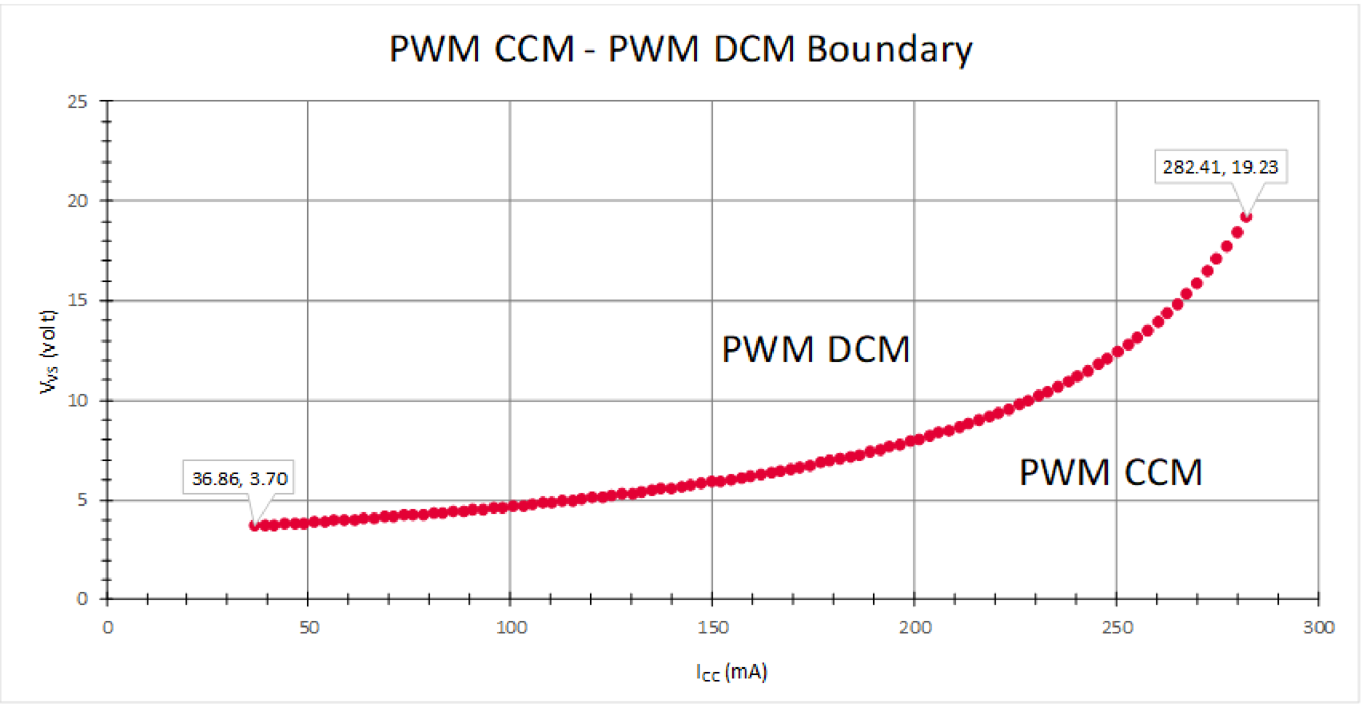

Figure 15 **PWM CCM – PWM DCM Boundary Example**

8.2 PWM DCM – PFM DCM boundary

At the boundary, the input voltage as a function of load current is described below and in Figure 16.

$$V_{vs}(I_{cc}) = \frac{V_{cc} - V_d}{2} + \frac{V_d + V_{cc}}{2 \cdot D1} \cdot \sqrt{D1^2 + \frac{8 \cdot I_{cc} \cdot L_{out} \cdot f_{osc}}{V_d + V_{cc}}}$$

With $V_{vs} = V_{vs\_min}$:

$$V_{vs\_min} = V_{vs,dec} = 3.7 \cdot volt$$

$$D1 = t_{on,min} \cdot f_{osc} = 17.16 \cdot \%$$

Example

$$D2 = \frac{f_{osc} \cdot t_{on,min} \cdot \left(V_{vs\_min} - V_{cc}\right)}{V_d + V_{cc}} = 2.08 \cdot \%$$

$$D3 = 1 - (D1 + D2) = 80.76 \cdot \%$$

$$V_{cc} = \frac{D1 \cdot V_{vs\_min} - D2 \cdot V_d}{D1 + D2} = 3.3 \cdot \mathrm{volt}$$

$$\Delta I_{L\_min} = \frac{\left(V_{vs\_min} - V_{cc}\right) \cdot t_{on,min}}{L_{out}} = \frac{\left(V_{vs\_min} - V_{cc}\right) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}} = 14.18 \cdot \mathrm{mA}$$

$$I_{cc\_min} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot \left(V_{vs\_min} - V_{cc}\right) \cdot \left(V_d + V_{vs\_min}\right)}{2 \cdot L_{out} \cdot (V_d + V_{cc})} = \frac{\left(V_{vs\_min} - V_{cc}\right) \cdot D1 \cdot (D1 + D2)}{2 \cdot L_{out} \cdot f_{osc}}$$

$$= \frac{1}{2} \cdot \Delta I_{L\_min} \cdot (D1 + D2) = 1.36 \cdot \mathrm{mA}$$

With $V_{vs} = V_{vs\_max}$:

$$V_{vs\_max} = \frac{V_d + V_{cc}}{t_{on,min} \cdot f_{osc}} - V_d = 19.23 \cdot \mathrm{volt}$$

$$D1 = t_{on,min} \cdot f_{osc} = 17.16 \cdot \%$$

$$D2 = \frac{f_{osc} \cdot t_{on,min} \cdot \left(V_{vs\_max} - V_{cc}\right)}{V_d + V_{cc}} = 82.84 \cdot \%$$

$$D3 = 1 - (D1 + D2) = 0 \cdot \%$$

$$V_{cc} = \frac{D1 \cdot V_{vs\_max} - D2 \cdot V_d}{D1 + D2} = 3.3 \cdot \mathrm{volt}$$

$$\Delta I_{L\_max} = \frac{\left(V_{vs\_max} - V_{cc}\right) \cdot t_{on,min}}{L_{out}} = \frac{\left(V_{vs\_max} - V_{cc}\right) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}} = 564.82 \cdot \mathrm{mA}$$

$$I_{cc\_max} = \frac{f_{osc} \cdot t_{on,min}^2 \cdot \left(V_{vs\_max} - V_{cc}\right) \cdot \left(V_d + V_{vs\_max}\right)}{2 \cdot L_{out} \cdot (V_d + V_{cc})} = \frac{\left(V_{vs\_max} - V_{cc}\right) \cdot D1 \cdot (D1 + D2)}{2 \cdot L_{out} \cdot f_{osc}}$$

$$= \frac{1}{2} \cdot \Delta I_{L\_max} \cdot (D1 + D2) = 282.41 \cdot \mathrm{mA}$$

Example

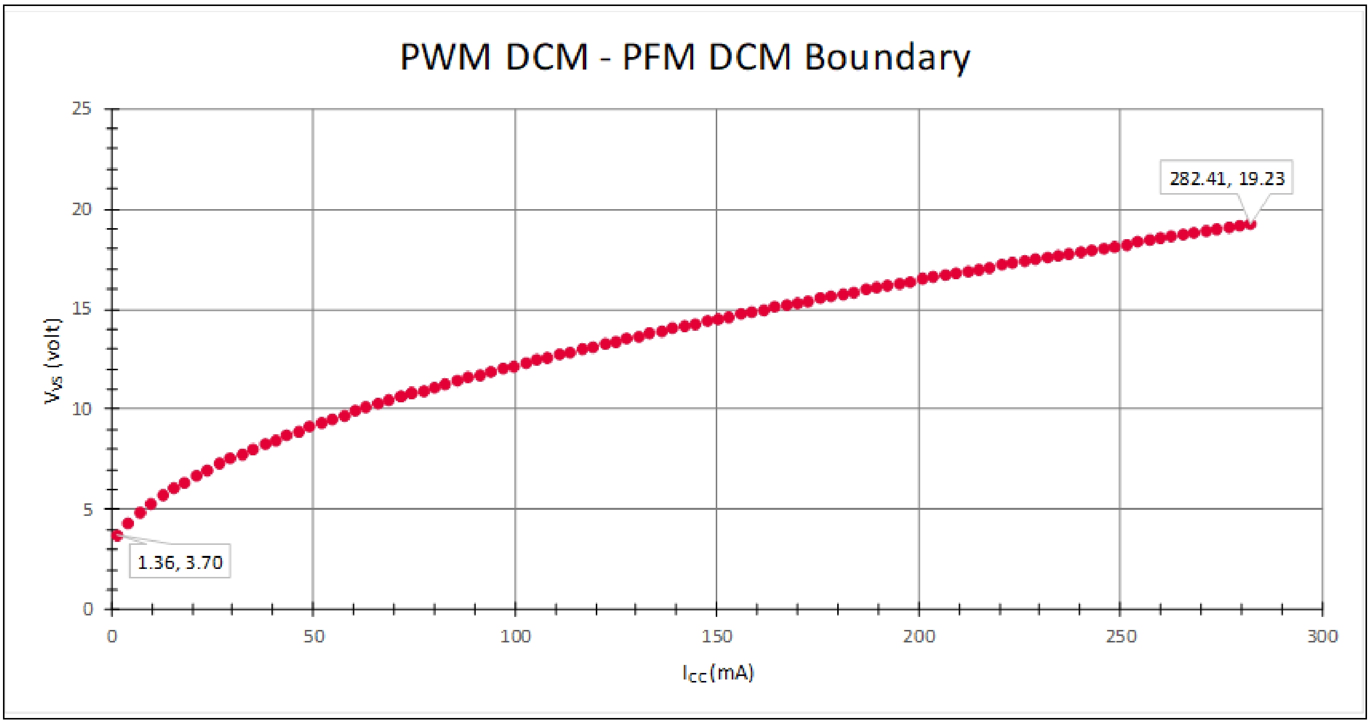

Figure 16 PWM DCM – PFM DCM Boundary Example

8.3 PWM CCM – PFM CCM boundary

At the boundary, the input voltage is described below and shown in Figure 17.

$$V_{vs} = \frac{V_{cc}}{f_{osc} \cdot t_{on,min}} = 19.23 \cdot \mathrm{volt}$$

$$D1 = t_{on,min} \cdot f_{osc} = 17.16 \cdot \%$$

$$D2 = 1 - D1 = 82.84 \cdot \%$$

$$\Delta I_L = \frac{(V_{vs} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{V_{cc} \cdot D2}{L_{out} \cdot f_{osc}} = 564.82 \cdot \mathrm{mA}$$

$$I_{cc\_min} = \frac{(1 - f_{osc} * t_{on,min}) \cdot V_{cc}}{2 \cdot L_{out} \cdot f_{osc}} = \frac{(V_{vs} - V_{cc})}{2 \cdot L_{out} \cdot f_{osc}} \cdot \frac{V_{cc}}{V_{vs}} = 282.41 \cdot \mathrm{mA}$$

$$I_{cc\_max} = I_{cc\_rated\_max}$$

Example

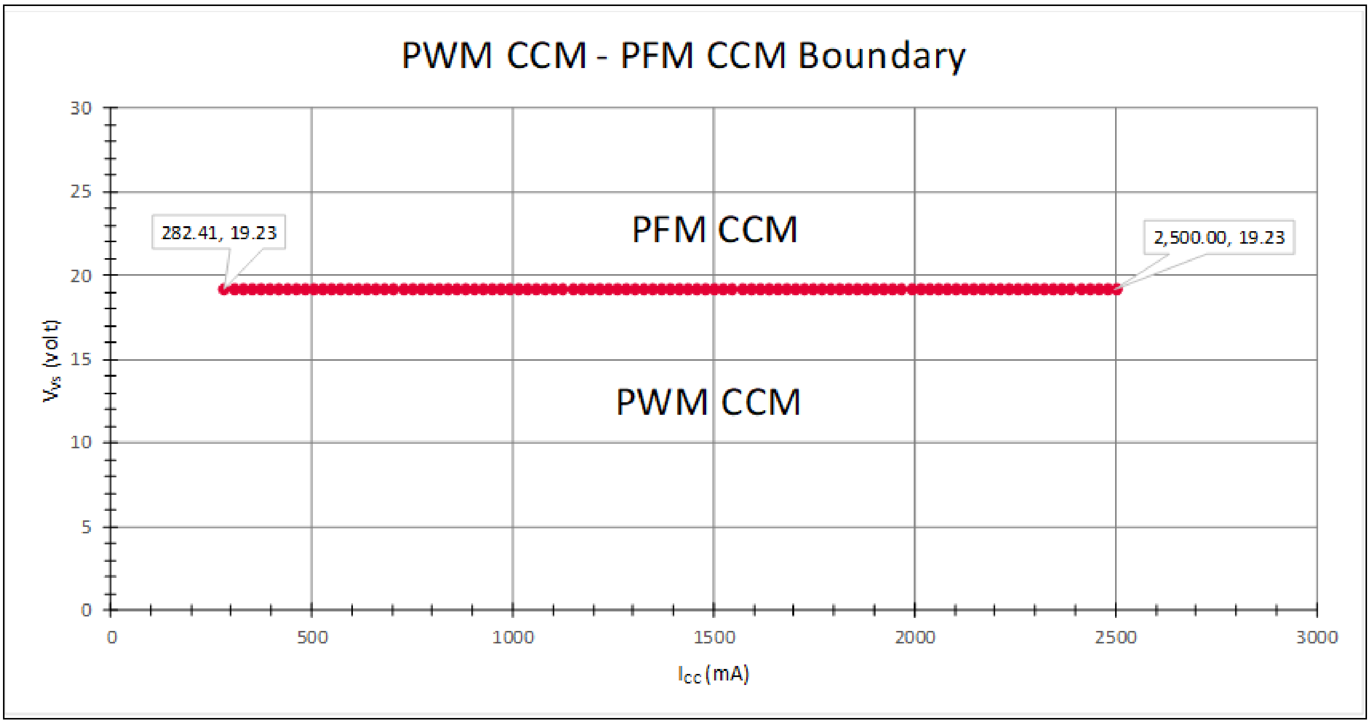

Figure 17 PWM CCM – PFM CCM Boundary Example

8.4 PFM CCM – PFM DCM boundary

At the boundary, the input voltage as a function of load current is described below and shown in Figure 18.

$$V_{vs}(I_{cc}) = V_{cc} + \frac{2 \cdot I_{cc} \cdot L_{out}}{t_{on,min}}$$

With $V_{vs} = V_{vs\_min}$:

$$V_{vs\_min} = \frac{V_d + V_{cc}}{f_{osc} \cdot t_{on,min}} - V_d = 19.23 \cdot \text{volt}$$

$$D1 = \frac{V_{cc} + V_d}{V_{vs\_min} + V_d} = 17.16 \cdot \%$$

$$D2 = \frac{D1 \cdot \left(V_{vs\_min} - V_{cc}\right)}{V_d + V_{cc}} = 1 - D1 = 82.84 \cdot \%$$

$$f_{pfm\_max} = \frac{D2 \cdot (V_d + V_{cc})}{t_{on,min} \cdot \left(V_{vs\_min} - V_{cc}\right)} = \frac{V_d + V_{cc}}{t_{on,min} \cdot \left(V_d + V_{vs\_min}\right)} = f_{osc} = 2.2 \cdot \text{MHz}$$

$$\Delta I_{L\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot t_{on\_min}}{L_{out}} = \frac{(V_{vs\_min} - V_{cc}) \cdot D1}{L_{out} \cdot f_{osc}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{osc}} = 564.82 \cdot \text{mA}$$

$$I_{cc\_min} = \frac{(V_{vs\_min} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}} = \frac{\Delta I_{L\_min}}{2} = 282.41 \cdot \text{mA}$$

With $V_{vs} = V_{vs\_max}$:

Example

$$V_{vs\_max} = V_{vs,dyn} = 42 \cdot \mathrm{volt}$$

$$D1 = \frac{V_{cc} + V_d}{V_{vs\_max} + V_d} = 7.86 \cdot \%$$

$$D2 = \frac{D1 \cdot (V_{vs\_max} - V_{cc})}{V_d + V_{cc}} = 1 - D1 = 92.14 \cdot \%$$

$$f_{pfm\_min} = \frac{D2 \cdot (V_d + V_{cc})}{t_{on,min} \cdot (V_{vs\_max} - V_{cc})} = \frac{V_d + V_{cc}}{t_{on,min} \cdot (V_d + V_{vs\_max})} = 1.007 \cdot \mathrm{MHz}$$

$$\Delta I_{L\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot t_{on\_min}}{L_{out}} = \frac{(V_{vs\_max} - V_{cc}) \cdot D1}{L_{out} \cdot f_{pfm}} = \frac{(V_{cc} + V_d) \cdot D2}{L_{out} \cdot f_{pfm}} = 1372.09 \cdot \mathrm{mA}$$

$$I_{cc\_max} = \frac{(V_{vs\_max} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}} = \frac{\Delta I_{L\_max}}{2} = 686.05 \cdot \mathrm{mA}$$

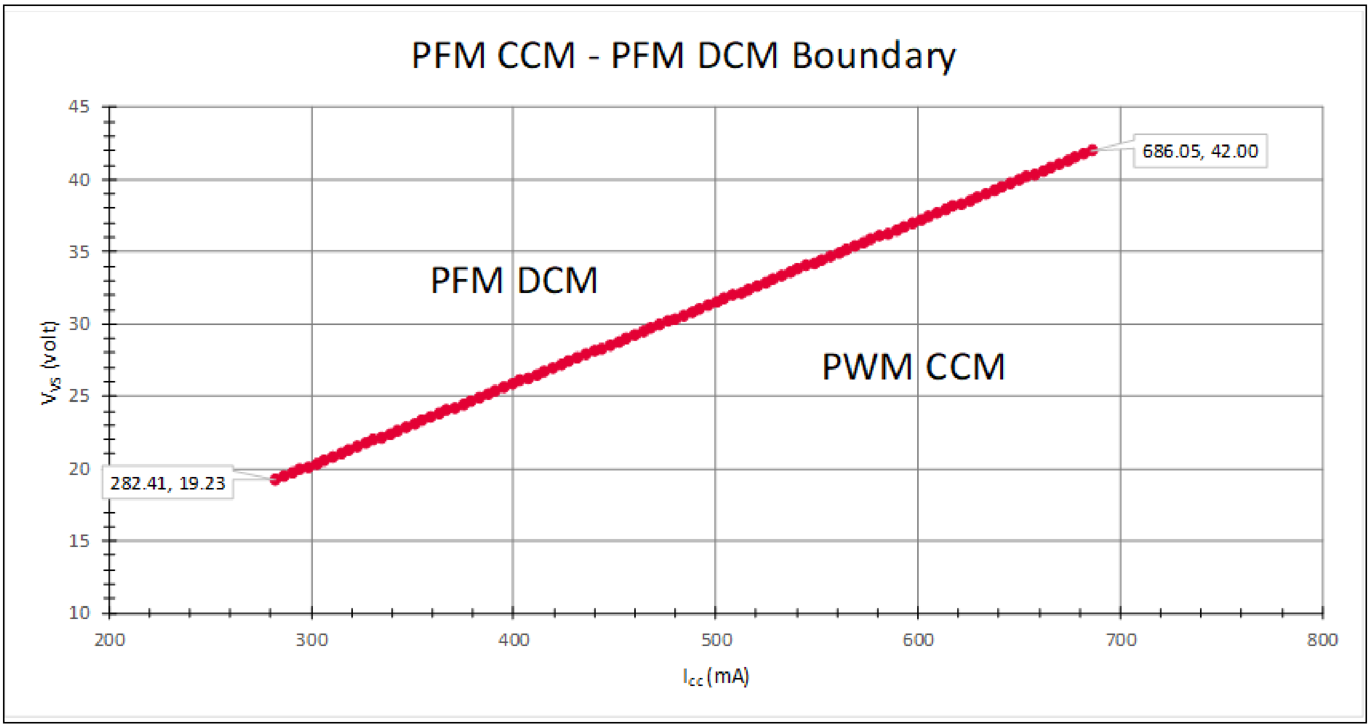

Figure 18 **PFM CCM – PFM DCM Boundary Example**

8.5 Operating mode map

The example composite operating mode map showing all four regions and boundaries is shown in Figure 19. Notice that all four regions are adjacent to each other (with no discontinuities) at a common point (282.41mA, 19.23V). This is because the DCM – CCM boundary conflict described in paragraph 5.1 was eliminated by making the synchronous rectifier body drain voltage (V_d) equal to zero.

Example

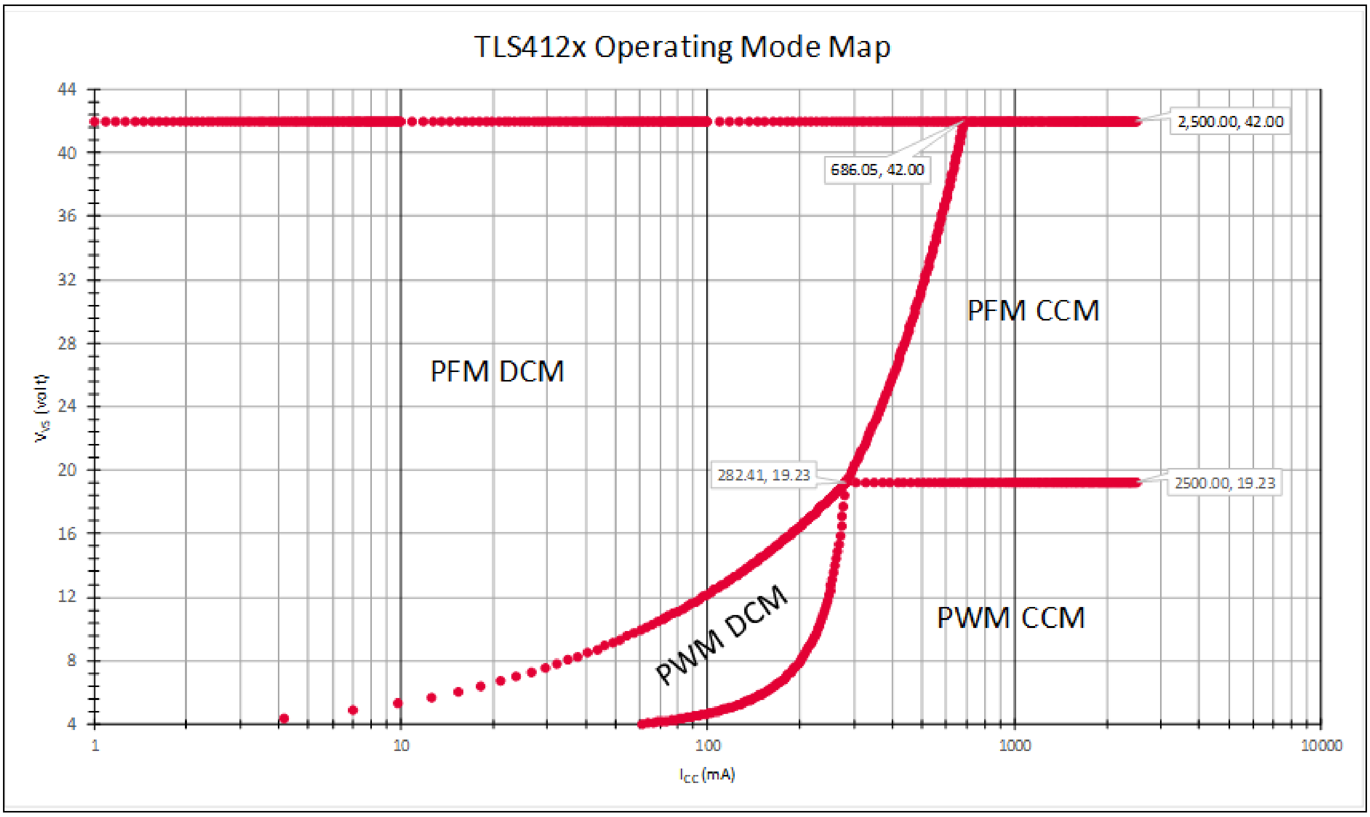

Figure 19 **Operating Mode Map Example**

9 Summary of the TLS412x boundary equations

The general operating mode boundary map is shown in Figure 20 (logarithmic x-axis). The TLS412x boundary equations follow where the synchronous rectifier body drain diode voltage is set to zero volts (paragraph 5.1).

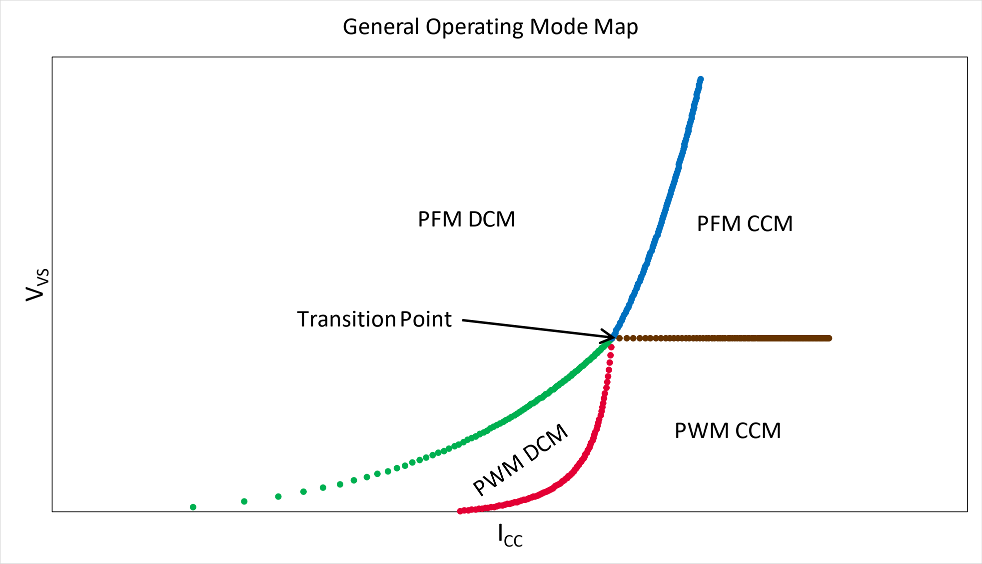

Figure 20 **General Operating Mode Map**

Transition Point:

$$V_{vs} = \frac{V_{cc}}{f_{osc} \cdot t_{on,min}} \qquad I_{cc} = \frac{(1 - f_{osc} \cdot t_{on,min}) \cdot V_{cc}}{2 \cdot L_{out} \cdot f_{osc}}$$

PWM CCM – PFM CCM Boundary (Brown):

$$V_{vs} = \frac{V_{cc}}{f_{osc} \cdot t_{on,min}}$$

PWM CCM – PWM DCM Boundary (Red):

$$V_{vs}(I_{cc}) = \frac{{V_{cc}}^2}{V_{cc} - 2 \cdot I_{cc} \cdot L_{out} \cdot f_{osc}} \qquad I_{cc}(V_{vs}) = \frac{V_{vs} - V_{cc}}{2 \cdot L_{out} \cdot f_{osc}} \cdot \frac{V_{cc}}{V_{vs}}$$

PWM DCM – PFM DCM Boundary (Green):

$$D1 = t_{on,min} \cdot f_{osc}$$

$$V_{vs}(I_{cc}) = \frac{V_{cc}}{2} \cdot \left[1 + \frac{1}{D1}\right] \cdot \sqrt{D1^2 + \frac{8 \cdot I_{cc} \cdot L_{out} \cdot f_{osc}}{V_{cc}}} \qquad I_{cc}(V_{vs}) = \frac{f_{osc} \cdot t_{on,min}^2 \cdot (V_{vs} - V_{cc}) \cdot V_{vs}}{2 \cdot L_{out} \cdot V_{cc}}$$

PFM CCM – PFM DCM Boundary (Blue):

$$V_{vs}(I_{cc}) = V_{cc} + \frac{2 \cdot I_{cc} \cdot L_{out}}{t_{on,min}} \qquad I_{cc}(V_{vs}) = \frac{(V_{vs} - V_{cc}) \cdot t_{on,min}}{2 \cdot L_{out}} \qquad f_{pfm}(V_{vs}) = \frac{V_{cc}}{t_{on,min} \cdot V_{vs}}$$

Revision history

Document version	Date of release	Description of changes
1.1	2020-04-09	• Changed title • Table 1 changed amp to A and volt to V • paragraph 6.4.2 simplified D1 equation
1.0	2020-04-02	Initial appnote

Trademarks
All referenced product or service names and trademarks are the property of their respective owners.

Edition 2020-04-09

Published by

Infineon Technologies AG

81726 Munich, Germany

© 2020 Infineon Technologies AG.
All Rights Reserved.

Do you have a question about this document?

Email: erratum@infineon.com

Document reference
Z8F68687934

IMPORTANT NOTICE
The information contained in this application note is given as a hint for the implementation of the product only and shall in no event be regarded as a description or warranty of a certain functionality, condition or quality of the product. Before implementation of the product, the recipient of this application note must verify any function and other technical information given herein in the real application. Infineon Technologies hereby disclaims any and all warranties and liabilities of any kind (including without limitation warranties of non-infringement of intellectual property rights of any third party) with respect to any and all information given in this application note.

The data contained in this document is exclusively intended for technically trained staff. It is the responsibility of customer's technical departments to evaluate the suitability of the product for the intended application and the completeness of the product information given in this document with respect to such application.

For further information on the product, technology, delivery terms and conditions and prices please contact your nearest Infineon Technologies office (**www.infineon.com**).

WARNINGS
Due to technical requirements products may contain dangerous substances. For information on the types in question please contact your nearest Infineon Technologies office.

Except as otherwise explicitly approved by Infineon Technologies in a written document signed by authorized representatives of Infineon Technologies, Infineon Technologies' products may not be used in any applications where a failure of the product or any consequences of the use thereof can reasonably be expected to result in personal injury.