

Dimming control using a PWM signal

XDP™ digital power

Abstract

This white paper explains how a pulse width modulation (PWM) signal is used for analog dimming of the output current of a light emitting diode (LED) lighting controller. An example for such a controller is the XDPL822x controller family from Infineon. This white paper provides information about how the PWM duty cycle maps to the output current and how the PWM duty cycle is measured in a digital controller. Possible faults are discussed which can cause flicker in light, and also solutions to these faults are provided.

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1 Introduction

To save energy, extend system life and enhance flexibility, the dimming of light has become a common requirement. The stability of light output is important as LEDs react very fast to any change of their driving current. Thus, any instability can cause visual flicker.

The usage of a PWM signal to control the light output of a power converter has several advantages compared to usage of an analog voltage level:

- › The information of the PWM signal can easily be transferred over an isolation barrier using a simple optocoupler. As the dimming information is coded in the timing of the edges of the signal, any tolerances as well as aging of the optocoupler causing a change in its gain has only minimal influence on the dimming information.
- › A digital controller can typically capture the timing of the PWM signal more accurately and with less effort than capturing a voltage level. For example, if the PWM signal uses a frequency of 1 kHz and is detected using a clock of 50 MHz, the granularity is $50 \text{ MHz}/1 \text{ kHz} = 50.000$. To achieve the same granularity for sensing of a voltage signal, a 16 bit analog-to-digital converter (ADC) is required ($2^{16} > 50000$).
- › Any circuitry for voltage levels can easily be affected by temperature. A temperature dependency of the circuitry is especially present if semiconductors are involved. For example, diodes typically change their forward voltage by -2.5 mV/K . For them, a temperature change of 60 °C can cause a voltage shift of 150 mV . If the dimming signal is coded by a signal between 0 V and 2 V , the temperature dependency causes an absolute error of 7.5 percent. The relative error (especially for low dimming voltages) will be even much higher.

This white paper provides information about different topics related to usage of a PWM signal for dimming control. First, the mapping of the PWM signal to an output current is shown. Secondly, the sensing of the PWM signal by a digital controller is described. Finally, possible flaws of the sensing and processing of the PWM signal are described, and solutions are presented to avoid any impact on the performance of the lighting application.

2 Mapping of PWM duty cycle to output current

If a PWM signal is applied to the output current directly, the PWM duty cycle relates proportional to the resulting current, e.g., a 30 percent duty cycle maps to 30 percent current and, a 60 percent duty cycle maps to 60 percent current as shown in Figure 1.

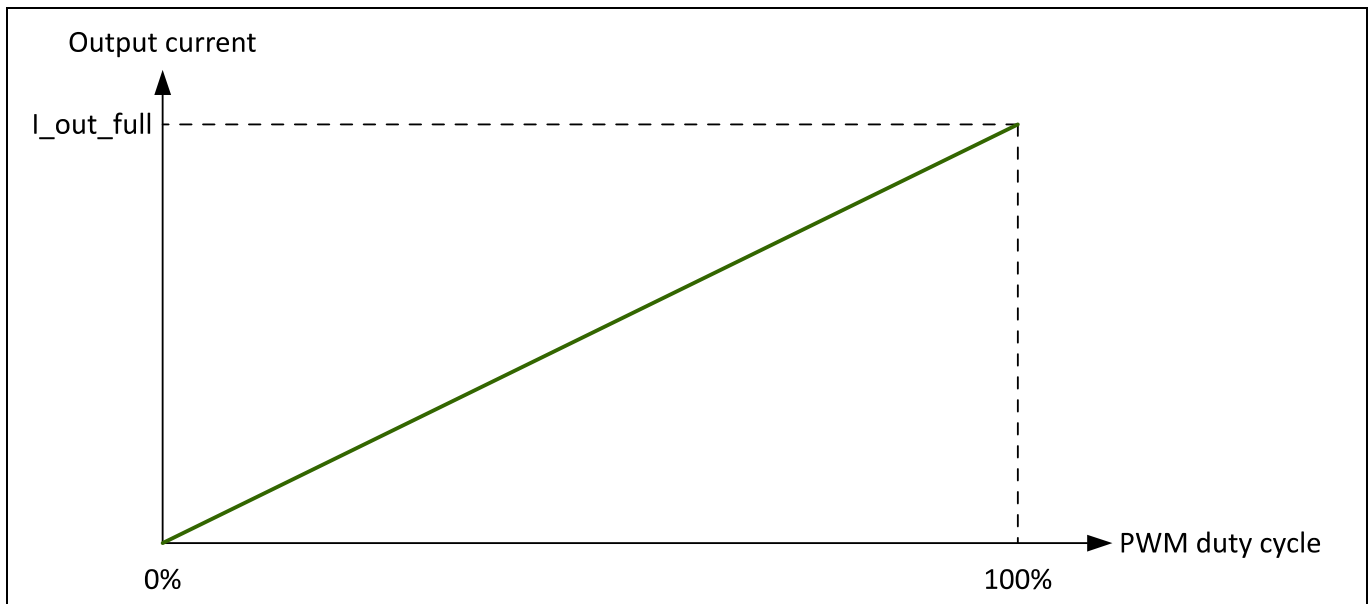


Figure 1 Direct mapping of a PWM signal to the output current

While this is the easiest mapping of a PWM signal to the output current, it has some disadvantages:

- › PWM signals with extreme duty cycles (e.g. 1 percent or 99 percent) can be affected by noise. Relative errors can become large and easily visible to the human eye, especially for low output currents.
- › Tolerances of components can cause part-to-part deviations. This can result in not all parts being able to reach extreme duty cycles. As a consequence, not all LED driver may be able to reach lowest and full light output.
- › The human eye is sensitive to relative changes in light intensity. The direct mapping allows no adaptation of the light output to this property of the human eye. As a consequence, when the PWM duty cycle is changed with a fixed rate in time, the relative changes in light will seem small at higher output currents and large for lower output currents.
- › Measurements of PWM duty cycles by digital controllers are limited by the sampling frequency of the digital signal processing.

Due to these facts, a different mapping of the PWM duty cycle to an output current is usually preferred. This mapping of the PWM duty cycle to an output current is called "dimming curve". Some possible dimming curves are shown in Figure 2.

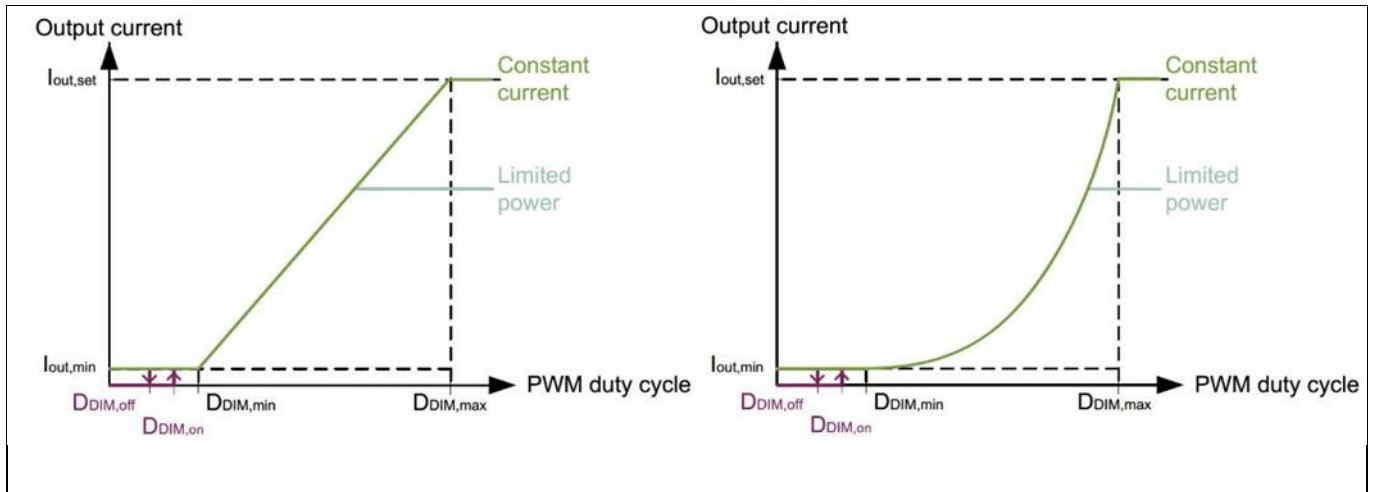


Figure 2 Dimming curves

A dimming curve may have different properties:

Dead bands:

Lower PWM duty cycles below a certain threshold $D_{DIM,min}$ are mapped to the lowest current. Higher duty cycles above another threshold $D_{DIM,max}$ are mapped to the full current. These dead bands ensure that lowest and full current can be reached independently from any tolerances. In between the thresholds, the current is interpolated. This causes a steeper curve compared to the direct mapping without dead bands. The relative change of current of a dimming curve with the dead bands is higher than the relative change of the PWM duty cycle of a direct mapping.

Shape:

The dimming curve between the dead bands can be either linear or eye-adapted:

- › The linear dimming curve ensures a proportional change of current with respect to the PWM duty cycle. This is the closest approximation of the direct mapping of the PWM duty cycle. In the special case of no dead bands, this maps directly to the output current.
- › As the human eye is sensitive to relative changes in light, the eye-adapted dimming curve ensures a constant relative change of output current with respect to PWM duty cycle. This requires an exponential dimming curve. To minimize the technical effort, the exponential curve can typically be approximated by a quadratic curve.

Direction:

The direction of the dimming curve defines the sign of the slope of the dimming curve:

- › **Normal:** a low PWM duty cycle maps to a low current, and a high PWM duty cycle maps to a high current.
- › **Inverted:** a high PWM duty cycle maps to a low current, and a low PWM duty cycle maps to a high current.

A change of the direction of a dimming curve may be beneficial in circuits which use an optocoupler as they might invert the polarity of the PWM signal.

3 Sensing the PWM duty cycle

The PWM duty cycle (see Figure 3) can be detected in two ways:

1. Measuring the positive pulse width (time between rising and falling edge) and negative pulse width (time between falling and rising edge), and calculating:

$$duty_cycle = \frac{positive_pulse_width}{positive_pulse_width + negative_pulse_width} \quad \text{Equation 1}$$

2. Measuring the positive pulse width (time between rising and falling edge) and the period (time between rising edges) and calculating:

$$duty_cycle = \frac{positive_pulse_width}{period} \quad \text{Equation 2}$$

The first way is preferred for the Infineon controllers with respect to implementation as the XDP™ hardware easily supports these measurements. Also, the equation is always valid while the second way may cause a division by zero and require case handling if the period is measured incorrectly or has not been measured at all.

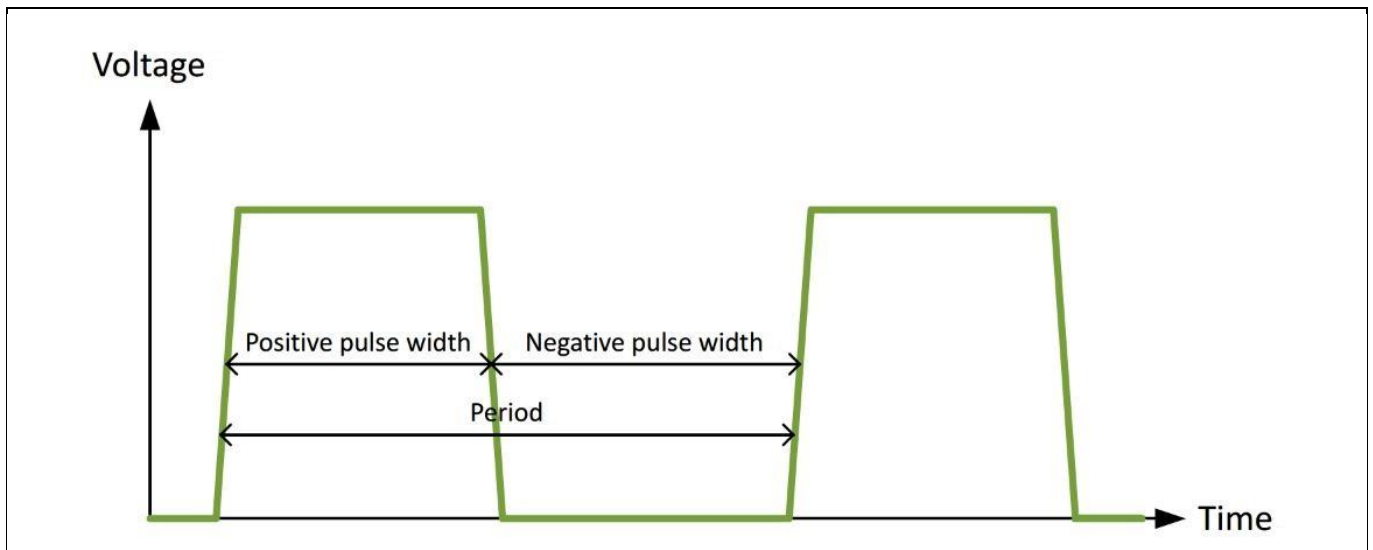


Figure 3 PWM signal

Due to capabilities of the used XDP™ hardware and the scheduling of firmware tasks, a positive or negative pulse width below a limit cannot be measured. For Infineon's XDPL8221, the firmware tasks are scheduled in intervals of typical 40 μs which limits the minimum pulse width to this duration¹ Depending on the frequency of the PWM signal, the minimum pulse-width-limits the usable PWM duty cycle can be the following²:

¹ XDPL8220 uses a scheduler interval of 32 μs

² Tolerances of the clock oscillator reduce these limits further.

- › For 2 kHz PWM signal: $40 \mu\text{s} * 2000 \text{ Hz} = 8 \text{ percent to } 92 \text{ percent}$
- › For 1.5 kHz PWM signal: $40 \mu\text{s} * 1500 \text{ Hz} = 6 \text{ percent to } 94 \text{ percent}$
- › For 1 kHz PWM signal: $40 \mu\text{s} * 1000 \text{ Hz} = 4 \text{ percent to } 96 \text{ percent}$

4 Potential errors in the usage of a PWM signal

The sensing and processing of the PWM signal can be disturbed by different effects. If periodic or random noise is present in the PWM signal itself or in the sensed duty cycle, the noise can propagate to the output current. Visible flicker can occur. Digital signal processing can reduce and avoid these effects.

Spikes or glitches

Spikes or glitches (see Figure 4), caused by for example switching gate drivers, can easily create false edges of the PWM signal and cause a wrong measurement of the pulse width. As the digital signal processing does not recognize any pulse width below a certain limit (e.g., for XDPL822x controller family this is 40 μ s), it is recommended to use a spike filter with the same filter duration (e.g., 40 μ s) to blank out any shorter spikes.

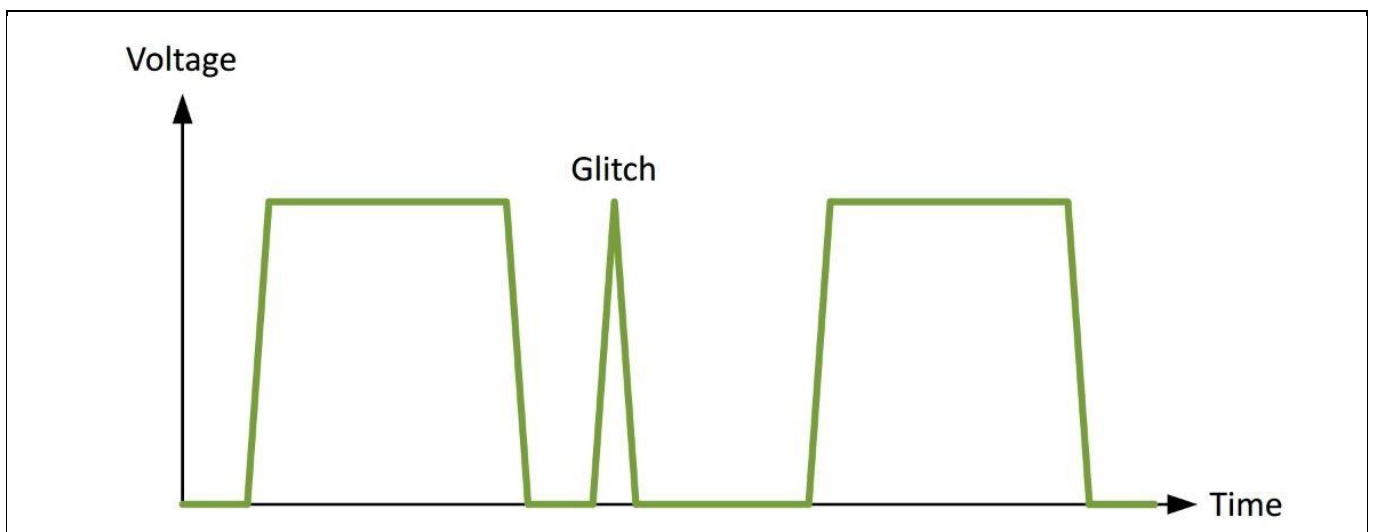


Figure 4 PWM signal with a glitch

Quantization noise

The duty cycle of the PWM signal is sensed with an asynchronous clock and is internally processed as a digital variable. Due to this, random quantization noise occurs as the duty cycle of the PWM signal does usually not map exactly to a digital representation (see Figure 5). The amplitude of the quantization noise depends on the granularity of the digital representation. Depending on the dimming curve, the quantization noise can be visible in light. To avoid flicker caused by quantization noise, a hysteresis can be used to suppress any change in duty cycle of only 1 bit.

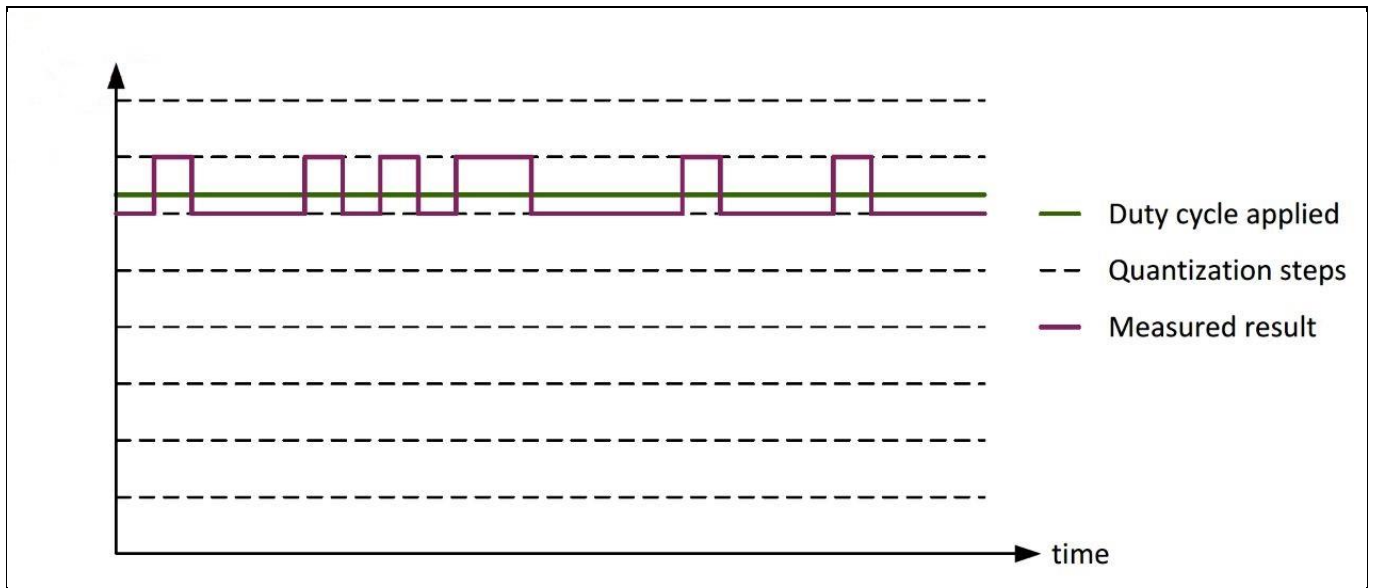


Figure 5 Effect of quantization noise on the PWM duty cycle

Example: the XDPL822x controller family processes the PWM duty cycle in $2^{11} = 2048$ steps. Therefore, a quantization noise of $1/2048 = \sim 0.05$ percent is expected for the duty cycle. If the system operates at for example 5 percent duty cycle and uses a linear dimming curve, the quantization noise causes for a 1 KHz PWM frequency a fluctuation of $0.05 \mu\text{s}$ (resolution) / $50 \mu\text{s}$ (duty period) = 1 percent deviation. Depending on the dimming curve, this can map to a higher fluctuation in light, especially if a steep linear dimming curve is used³.

Jitter of the PWM signal

The PWM signal may not be stable over time. Two typical sources of instability are temporal changes of the duty cycle (duty cycle jitter) or temporal changes of frequency (frequency jitter), as shown in Figure 6. Both types of jitter can create visible flicker in light, especially at low output currents if a linear dimming curve is used.

Example: assume a PWM signal with a frequency of 1 kHz, a duty cycle of 10 percent and a duty jitter of $4 \mu\text{s}$. This results in a variation of duty cycle of 0.4 percent which may seem rather small. However, the human eye is sensitive to the relative change in light. Assuming a linear dimming curve without dead bands, this jitter creates a relative change in light output of $0.4 \text{ percent} / 10 \text{ percent} = 4 \text{ percent}$ which is visible in light.⁴

³ As the human eye can only sense relative differences in light of more than 2.7 percent, no flicker is expected for the XDPL822x controller due to quantization noise.

⁴ The human eye can typically sense relative differences in light of more than 2.7 percent.

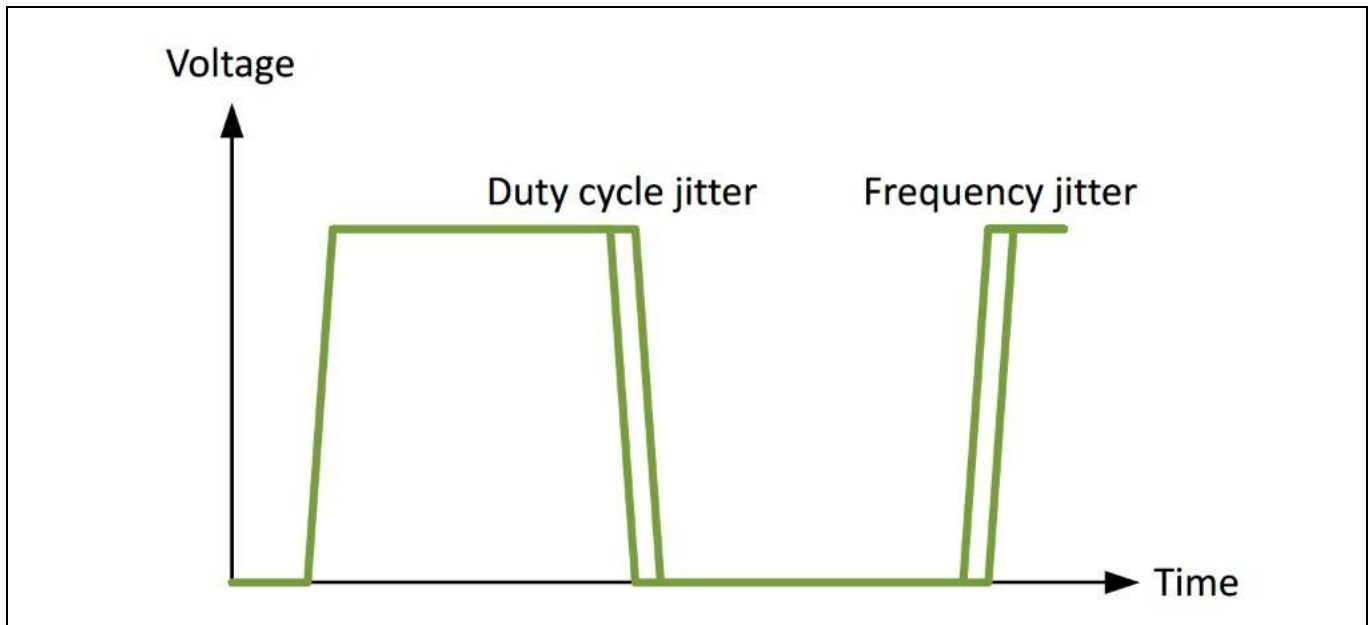


Figure 6 Multiple periods of a PWM signal with jitter overlaid

To suppress fluctuations in duty cycle, different methods can be used:

- › The sensed duty cycle can be filtered (e.g., using a finite or infinite impulse response filter). This will remove any fast reactions of the controller to jitter of a PWM signal. A disadvantage is that any signal processing for the filter introduces a delay. As a consequence, a too strong filter is not desired as it can create a noticeable latency in the transient response (e.g. if the dimming level is changed by intention). Also, a filter should not be applied to the PWM signal during the start of the controller as it can significantly delay the time-to-light.
- › A hysteresis can be applied to the sensed signal to ignore any smaller deviations below a certain threshold. This still allows to react immediately to larger transients. A disadvantage of a hysteresis is that the controller will show no reaction to slow transients of a clean PWM signal for a limited time if the dimming direction is changed (dimming up after previously dimming down or vice versa).
- › The methods above can be combined to trade off the advantages and disadvantages of both methods.

Impact of other features on the dimming curve

Some feature of a lighting controller can cause deviations of output current measured from the ideal dimming curve, as shown in Figure 7. The following explanations refer to a normal dimming curve (low current at low PWM duty cycle):

- › If the controller features a limited power mode and the full output current would be above the power limit at some output voltages ($V_{out} * I_{out,full} > P_{out,set}$), the output current will not reach the full output current. The controller will limit the high dead band to a lower current level of $I_{out} = P_{out,set} / V_{out}$. As the level of the high dead band is lower than the full current, the controller will enter this dead band already at a lower PWM duty cycle than the $D_{DIM,max}$ configured.

- › If the dimming curve is configured to a minimum current which cannot be achieved at all output voltages due to a minimum power limit ⁵($V_{out} \cdot I_{out,min} < P_{out,min}$), the output current will not reach the minimum output current for these cases. The controller will be limited to higher low dead band at $I_{out} = P_{out,min}/V_{out}$. As the level of the low dead band is higher than the minimum current, the controller will enter this dead band already at a higher PWM duty cycle than the $D_{DIM,min}$ configured.
- › A hysteresis for the sensing of the PWM duty cycle can cause an offset of the dimming curves from the ideal curve. This effect is strongest for a clean PWM signal without any jitter. If the PWM signal has random jitter, the noise will reduce the visible hysteresis between dimming curves.

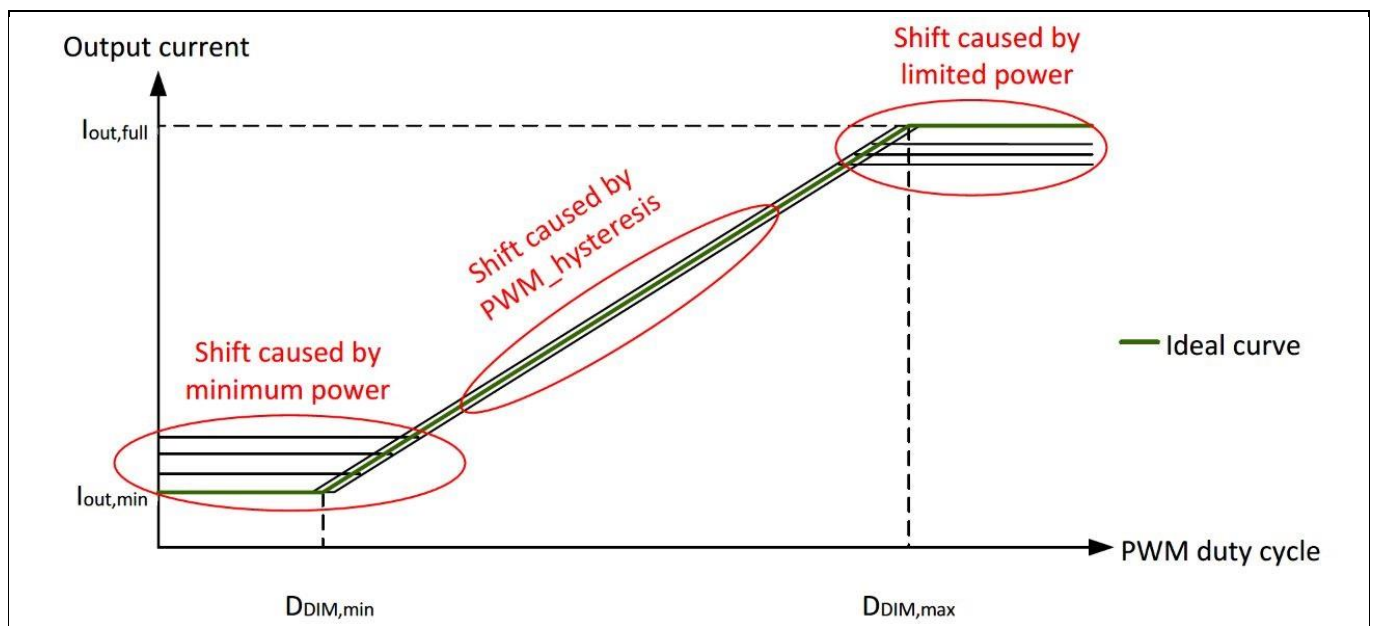


Figure 7 Deviations of the dimming curve from the ideal case

⁵ Please, note that a minimum power level may not be a fixed value, but may depend on other parameters, especially on the bus voltage

5 Summary

It has been shown that PWM dimming provides some advantages, however few corner cases might require some extra consideration. This paper describes how to deal with these cases.

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