

Buck Converter Selection Criteria

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Introduction

Richtek has a wide range of Step-Down DC/DC (Buck) converters, but selecting the right Buck converter for your application can be a challenge. This guide will help you to distinguish the different Buck converter types, and highlights the key parameters which need to be considered for choosing the optimal part for your application.

Buck converter basics

Buck converters are switch-mode step-down converters which can provide high efficiency and high flexibility at higher V_{IN}/V_{OUT} ratios and higher load current. The basic circuit is shown in Figure 1. Most Buck converters contain an internal high-side MOSFET Q1 and low-side synchronous rectifier MOSFET Q2, which are in turn switched on and off via internal duty-cycle control circuit to regulate the average output voltage. The switching waveform is filtered via an external LC filter stage. A feedback loop senses the output voltage and controls the duty-cycle of the high-side MOSFET, thereby regulating the output voltage. Asynchronous parts do not have an internal low-side MOSFET, and need an external Schottky diode from switch node to ground. Due to the fact that the MOSFETs are either ON or OFF, they dissipate very little power, and the duty-cycle control makes large V_{IN}/V_{OUT} ratios possible. The internal MOSFETs $R_{DS(ON)}$ mainly determines the current handling capabilities of the Buck converter, and the MOSFET voltage ratings determine the maximum input voltage.

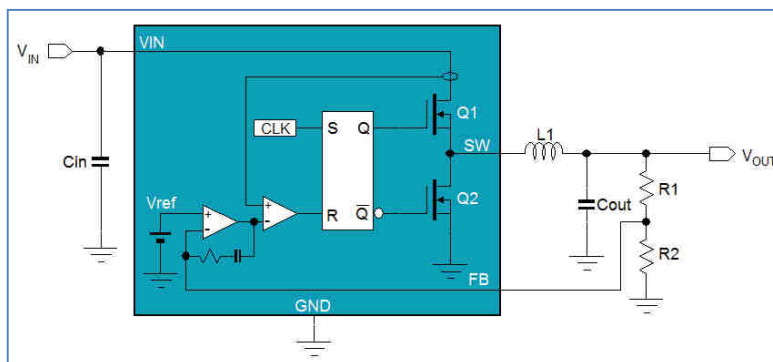


Figure 1. Buck converter basic circuit

Voltage and current rating selection

Application input voltage

When choosing a Buck converter, the input voltage range is the first parameter that needs to be considered. Richtek Buck converters can be divided in three main groups:

- LV Buck with V_{IN} range from 2.5V ~ 5.5V
- 18V HV Buck with V_{IN} range from 4.5V ~ 18V
- HV range with V_{IN} range 4.5V up to 36V.

Many parts in the LV buck converter range are optimized for running off single cell Li-Ion batteries, but can also be used for supplies running from 5V rails.

The 18V rated parts are normally used for applications that run from 12V supply rails, but their wide voltage range makes it possible to run them from 5V rails as well.

The 21V / 23V / 24V and 36V parts have a very wide application range. Quite often these parts are selected when the input voltage rail has a wide tolerance, or when it has voltage peaks and dips that the Buck converter needs to be able to handle. The 36V parts are often used in applications that need to run from industrial supply voltage rails like 24Vdc, or 13.5V car battery powered automotive applications with high supply voltage surge.

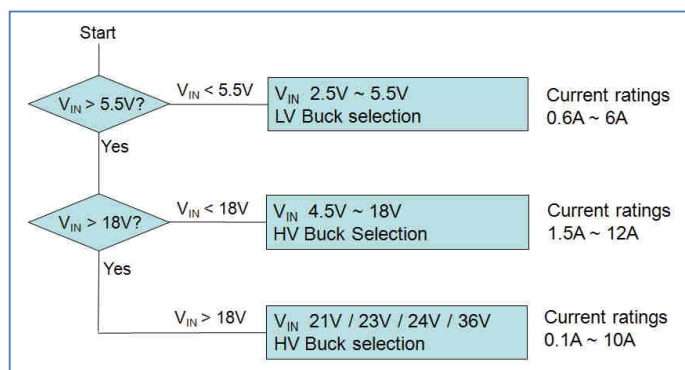


Figure 2. Richtek Buck converter selection flow

Application current consumption

When considering the Buck converter current rating, there are two factors to consider: The application *average current* consumption and the application *peak current*.

The application **average** current should always be lower than the device rated current as mentioned in the datasheet. How much lower depends on the device power dissipation and application thermal conditions. The application average current will determine the average heat in switching MOSFETs which is related to conduction losses and switching losses. Conduction losses are related to the internal MOSFET $R_{DS(ON)}$: The MOSFET conduction losses are $I^2 \cdot R_{DS(ON)}$. When the high-side and low-side $R_{DS(ON)}$ are not the same, the application step-down ratio should also be considered to check the power dissipation in high-side and low-side MOSFETs. Switching losses are mostly related to the current, the input voltage and the switching frequency. In most standard applications, the switching losses are roughly 30% of the total losses, but in applications with higher input voltage or high frequency, the switching losses can increase considerably. The application total power losses can be derived from the datasheet efficiency curve: $P_{LOSS} = \frac{(1-\eta)}{\eta} (V_{OUT} \cdot I_{OUT})$. Please note that this power losses includes the inductor losses as well, which are normally around 10% ~ 20% of the total losses. The IC maximum allowed power dissipation depends on the IC package, the layout and the application maximum ambient temperature. Layouts with more copper connected to IC pins and package thermal pad can be helpful dissipate more power.

The application **maximum** current can normally be at the same level as the device rated current as mentioned in the datasheet, sometimes even a bit higher. The designer should make sure that the over-current protection (OCP) is never triggered during maximum application load current. Buck converters sense the inductor peak current (or valley current in some ACOT™ devices), and datasheet OCP current values refer to these inductor peak or valley current levels. The difference between load current and inductor peak or valley current is $\frac{1}{2}$ the inductor ripple current, so be sure to include this when checking the application maximum load current in relation to OCP current levels.

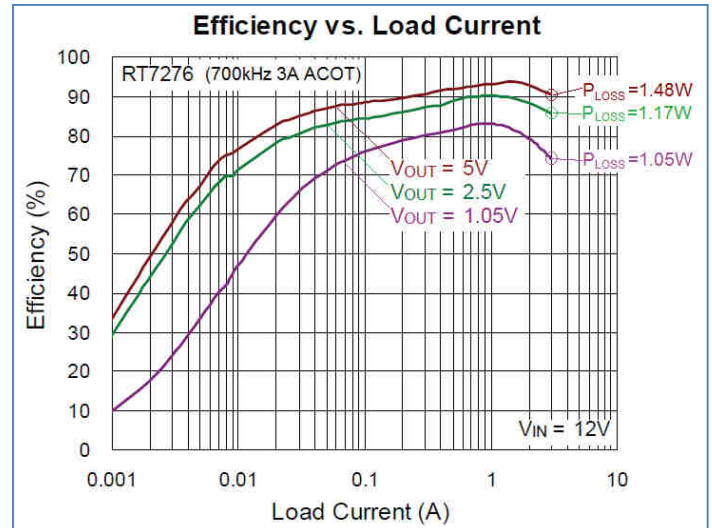


Figure 3. Efficiency curves at different output voltages

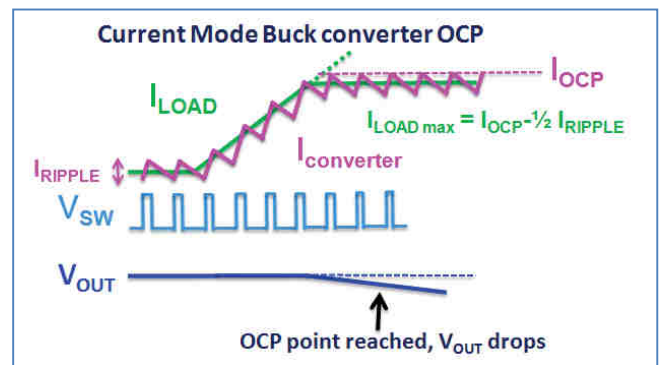


Figure 4. Buck converter over-current protection

Light load efficiency (PSM / Force-PWM selection)

For supply rails that need to be active in low power standby modes, it is desirable to make the Buck converter efficiency at light load as high as possible. Force-PWM* Buck converters keep the switching frequency fixed over the entire load range. The high switching frequency at light load will mean that the majority of losses at light load will be caused by switching losses. Buck converters with enhanced light load efficiency will reduce their switching frequency at light load; this is often called Pulse Skip Mode (PSM**). The operation principle is as following: When the load reduces, the inductor current valley reaches zero current at a certain point. Force-PWM parts keep the low-side MOSFET conducting, which will make the inductor current going negative. In PSM parts, the low-side MOSFET is switched off when the inductor current reaches zero, and the switch node floats until the next time the high-side MOSFET is switched on. The minimum ON time of the high-side MOSFET determines the inductor peak current and average inductor current can only be reduced by reducing the switching frequency; i.e. by inhibiting the internal clock, thereby 'skipping pulses'. Voltage regulation in PSM is accomplished by comparing the output voltage ripple valley with the internal reference. PSM will reduce the converter switching frequency to very low values at light load; down to a few kHz. This reduces switching losses, thereby increasing the light load efficiency considerably.

PSM does have some disadvantages:

- The output ripple voltage is a low frequency triangular waveform which can be hard to filter. Depending on PSM regulation criteria and component values, the PSM output voltage ripple amplitude can be higher than in PWM mode. Some loads may be sensitive to this.
- When a converter running in PSM suddenly sees a load step, it quickly has to switch from PSM to PWM mode. This transition will result in larger output voltage undershoots compared to converters that always run in force-PWM mode.
- In PSM, the regulated average voltage is slightly higher ($\sim 1\%$) compared to PWM mode.
- Due to the variable switching frequency, PSM can sometimes cause interference in sensitive adjacent circuits

If the application does not need enhanced light load efficiency, it is better to select Force-PWM parts, which will provide stable operation conditions over the full load range.

*In some Richtek documents, Force-PWM mode is called PWM mode or Continuous Operation Mode.

** In some Richtek documents the Pulse Skip Mode is called PWM/PSM or DEM or Discontinuous Operation Mode.

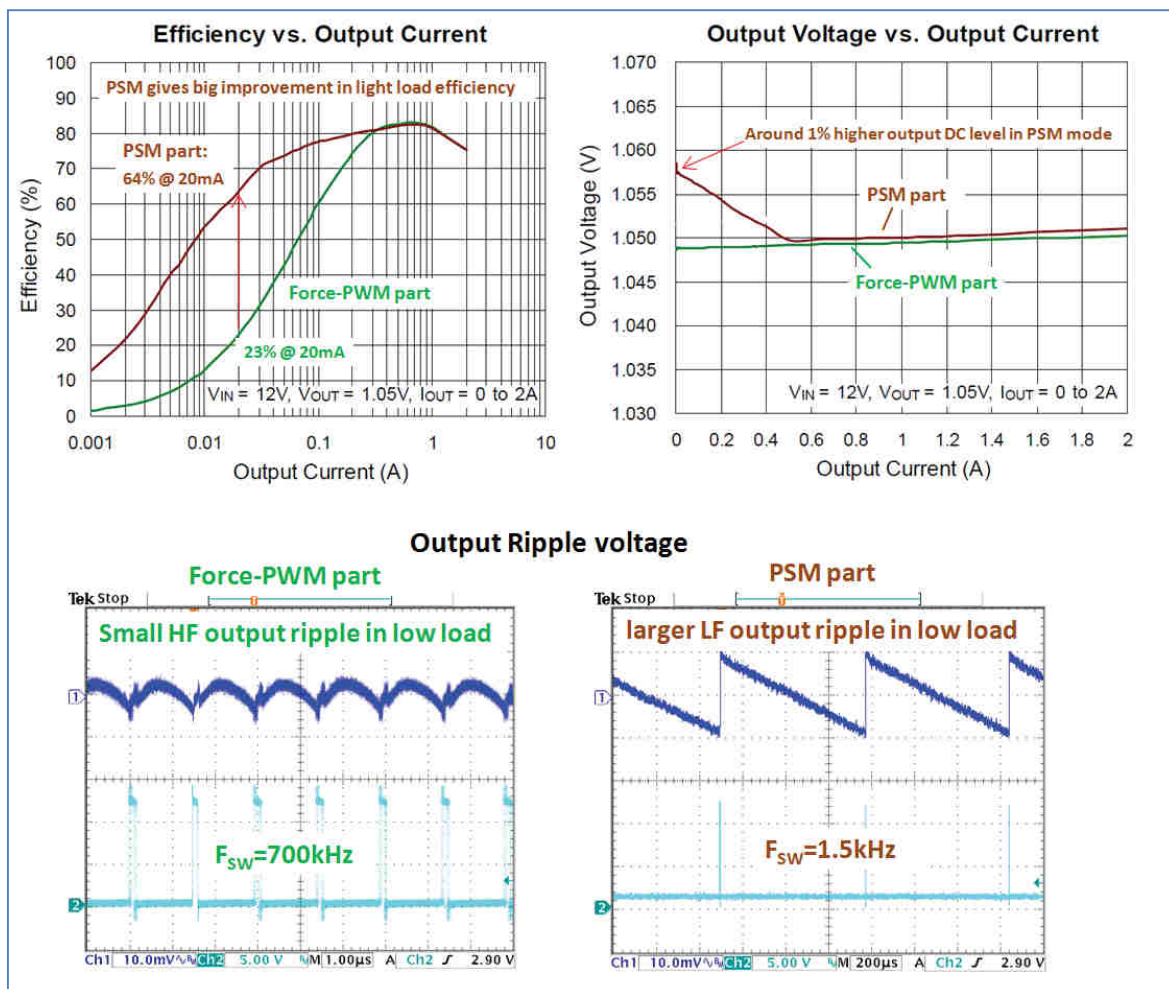


Figure 5. PSM advantages and disadvantages

Switching Frequency considerations

The switching frequency of Buck converters is important parameter to consider. Higher switching frequency makes it possible to use smaller inductor and capacitors, and improves the step load behaviour of the converter. However, it also increases switching losses and extends the EMI radiation frequency range. Higher switching frequency can also limit the maximum step-down ratio that can be achieved: The minimum duty-cycle is limited by the converter minimum ON time and the frequency:

$$\delta = \frac{t_{ON}}{T_{PERIOD}} = t_{ON} \cdot F_{SW}, \text{ so } \delta_{min} = t_{ON min} \cdot F_{SW}$$

For example, at a given $t_{ON(MIN)} = 100\text{nsec}$, a 1.2MHz converter has a minimum duty-cycle of 12%, and would not be able to step down from 12V to 1.2V. An 800kHz converter would have a minimum duty-cycle of 8% and can step-down 12V to 1.2V.

Very high frequency Buck converters ($> 1\text{MHz}$) are often used when the input voltage is relatively low; (5V or lower) because the switching losses at low V_{IN} are lower, and the maximum step down ratios for these applications are lower as well.

For most 12V applications, switching frequencies between 500kHz ~ 800kHz are suitable, providing a good compromise between switching losses and component size.

In high current applications with higher input voltages ($> 18\text{V}$) it is better to use switching frequencies lower than 500kHz to reduce the switching losses and still allow high step-down ratios.

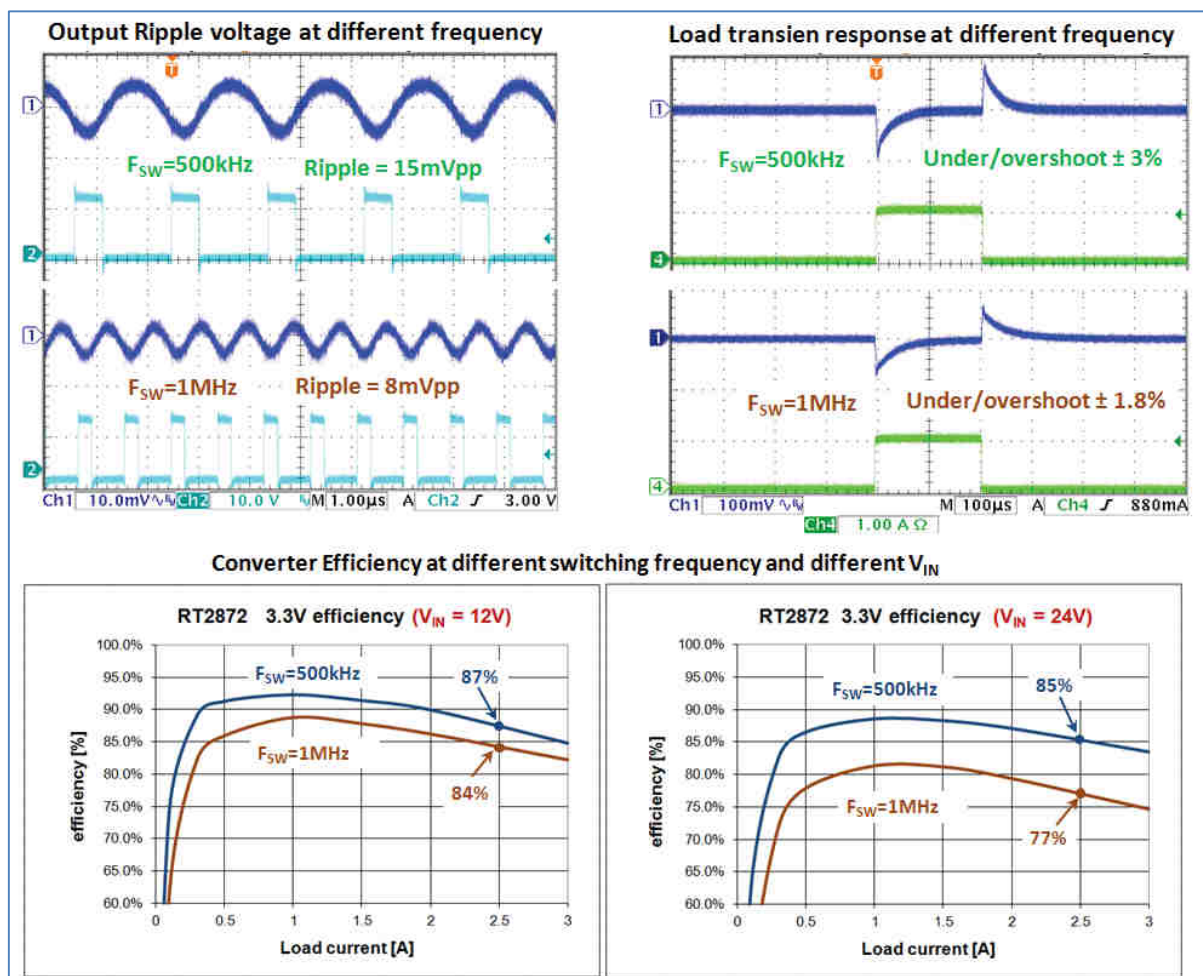


Figure 6. Buck converter switching frequency influence on ripple, transient response and efficiency

Buck converter control topology selection criteria

The Richtek DC/DC portfolio contains a wide range of Buck converters with different control topologies, including Current Mode (CM), Current Mode-Constant On Time (CMCOT) and Advanced Constant On Time (ACOT™) control topologies. Each topology has its advantages and drawbacks, so when selecting a Buck converter for an application, it is good to understand the characteristics of each topology.

Current Mode control

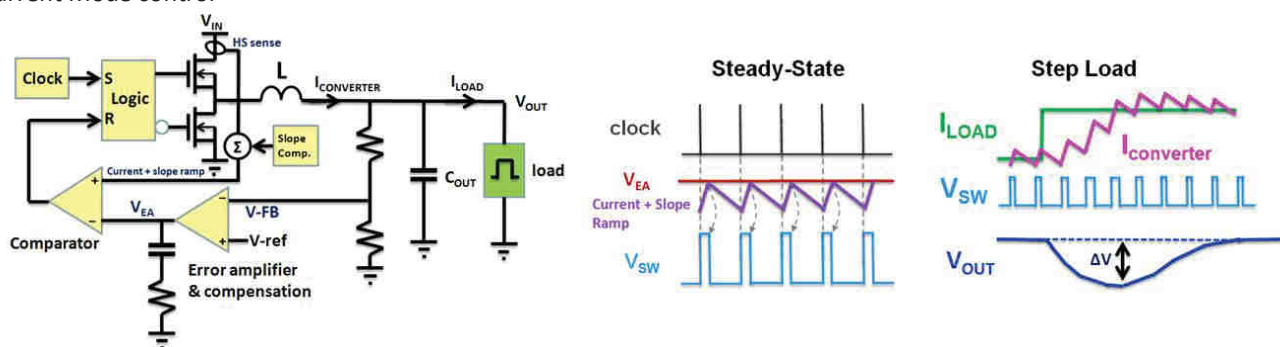


Figure 7. CM Buck converter basic circuit diagram and operation waveforms

Current Mode converters have an internal clock generator, an error amplifier and current sense. The error signal is compared with the sensed peak current and controls the on time of the upper MOSFET. The start of a new switching cycle is determined by the clock signal, so the system runs in fixed switching frequency. Control bandwidth is usually around $1/10^{\text{th}}$ of the switching frequency.

Current mode Buck converter	
Advantages : <ul style="list-style-type: none"> • Fixed frequency operation • Can be Synchronized to ext. clock • Established technology • Stable with MLCC 	Disadvantages : <ul style="list-style-type: none"> • Slow response to fast load steps • Needs error amplifier compensation • Needs slope compensation

If the application load current is relatively steady, you can use current mode Buck converters. If the system is susceptible to noise at certain frequencies, you also may want to use a current mode Buck converter, and maybe synchronize it to an external clock signal to set the switching frequency very precisely. Many current mode Buck converters in the LV input range support 100% duty-cycle operation, which makes it possible to run these Buck converters at V_{IN} very close or equal to V_{OUT} .

Current Mode - Constant On Time control

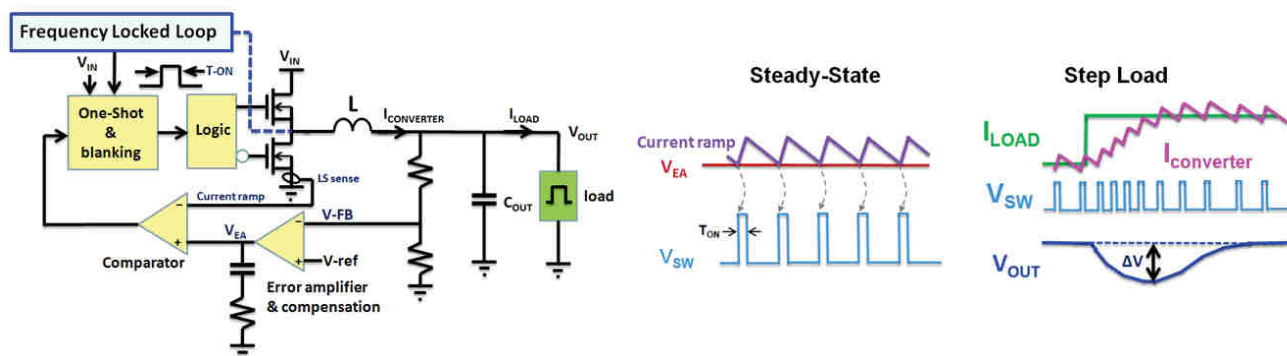


Figure 8. CMCOT Buck converter circuit diagram and operation waveforms

CMCOT Buck converters do not have an internal clock; the upper MOSFET always conducts for a pre-defined fixed ON time. The duty-cycle is regulated by changing the OFF time of the upper MOSFET. CMCOT converters also contain a current sense and error amplifier, but now the falling slope of the current is compared to the output of the error amplifier. The fact that the system does not need to wait for a next clock-cycle makes it possible to react more quickly to sudden step loads; as soon as the output voltage drops and the error amplifier voltage rises above the falling current slope, a new ON time is triggered and the inductor converter current rises again.

Richtek Current Mode-COT (CMCOT) Buck converter	
Advantages: <ul style="list-style-type: none"> • Fast response to load steps • Low Side current sense • Small minimum ON time allows small duty-cycles. • Constant average frequency • Stable with MLCC • Does not need slope compensation 	Disadvantages: <ul style="list-style-type: none"> • Needs error amplifier compensation • Cannot be Synchronized to ext. clock • Some frequency deviation during load transients.

If the application load has moderate transient load conditions, you may want to choose a CMCOT topology Buck converter, to reduce output voltage fluctuation during load transients. CMCOT converters can achieve 20 ~ 30% better load transient behavior when compared to standard current mode Buck converters. CMCOT also is less sensitive to noise in low duty-cycle applications. Due to its very small minimum ON time, the CMCOT Buck converter can be used for applications with larger step-down ratios. CMCOT converter switching frequency will show some deviation during load transients.

Advanced Constant On Time control (ACOT™)

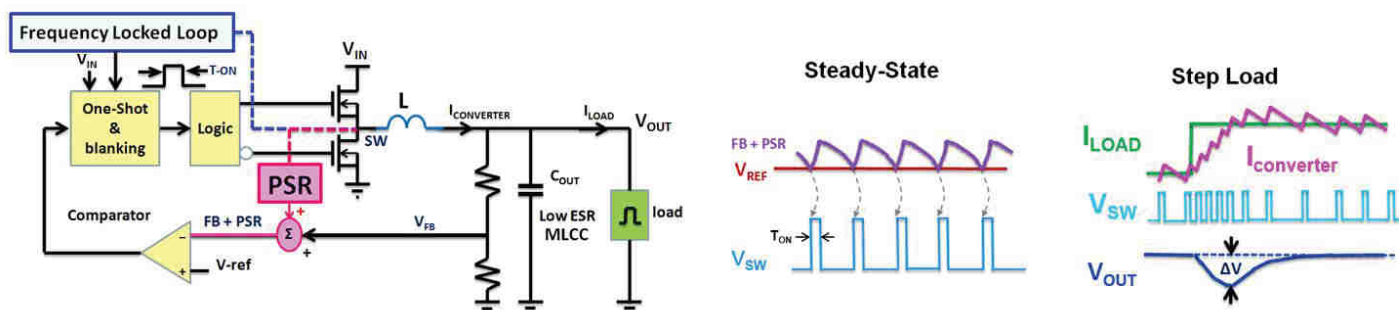


Figure 9. ACOT Buck converter circuit diagram and operation waveforms

ACOT converters do not contain an error amplifier or current sense; they directly compare the feedback signal (DC level + ripple voltage) with an internal reference. When the feedback signal falls below the reference, a new fixed ON time is generated and inductor current rises. If the output voltage has not recovered, another ON time is generated after a short blanking period until the inductor current matches the load current and output voltage is at its nominal level again. To make the converter stable with low ESR ceramic output capacitors, an internally generated Pulse Shaping Regulator (PSR) ramp

signal is added to the ripple and the DC level from the converter output. These are summed and then compared with an internal reference. When this summed voltage drops below the reference, the comparator triggers the ON time generator. A sudden drop in output voltage will immediately result in a new ON time, and the converter can generate successive ON times as long as the output voltage has not recovered. This makes the ACOT topology reaction speed to load transients extremely fast.

A special frequency locked loop system will slowly adjust the ON time to regulate the average switching frequency to a defined value.

Richtek Advanced-COT (ACOT™) Buck converter	
Advantages: <ul style="list-style-type: none"> Extremely fast response to load steps Does not need current sense Small minimum ON time allows small duty-cycles. Constant average frequency Stable with MLCC Does not need slope compensation 	Disadvantages: <ul style="list-style-type: none"> Cannot be Synchronized to ext. clock Large F_{SW} deviation during dynamic load

If the application load shows severe fast load transients (like seen in Core and DDR rails) it is best to choose ACOT Buck converters, which can improve load transient behavior by a factor 2 to 4, and make it possible to use smaller output capacitors. They are especially suitable for low duty-cycle applications. Due to their very small minimum ON time, ACOT Buck converters with high switching frequencies can be used in applications with large step-down ratios. ACOT converter switching frequency can show considerable deviation during load transients. But the absence of loop compensation and slope compensation and the extremely fast loop response makes ACOT designs simple, flexible and cost effective.

Other Buck converter selection criteria

External soft-start

All Richtek Buck converters have a soft-start function. After enabling the converter, the duty-cycle is gradually increased to allow a smooth rising output voltage, which avoids inrush current due to sudden charging of the output capacitors. Converters with internal soft-start have a fixed soft-start time. If the application uses very large output capacitance or requires a specific soft-start time, it is better to select a converter with externally programmable soft-start; the soft-start time can be set by an external capacitor.

External compensation

Current mode converters need error amplifier compensation to ensure stable operation. The type-II compensation components determine the converter bandwidth and the phase boost frequency. Converters with external compensation have more flexibility in setting the desired bandwidth and phase margin with different types of output capacitors over a wider range of input and output voltage conditions.

Programmable frequency

Some converters have a programmable frequency function: The switching frequency can be set by means of an external resistor.

This gives more flexibility in choosing the best switching frequency for the application; higher frequency to reduce ripple or component size or get better transient behavior, or lower frequency to improve efficiency or reduce higher harmonics.

External sync input

Some current mode converters have an external sync input that allows the internal clock to be synchronized to an external clock signal. This makes it possible to set the switching frequency at a very precise value (for avoiding noise at sensitive frequency bands), and also make it possible to run several converters at the same frequency.

Low-Dropout mode or 100% duty-cycle mode

Many current mode Buck converters from the LV series have Low Dropout mode function: When the input voltage drops, these Buck converters gradually increase the duty-cycle and will continuously switch-on the high side MOSFET when the input voltage drops below the regulated output voltage. This function is especially suitable in battery powered applications, and can extend application operation time when the battery is almost depleted.

Power Good function:

The Power Good function will monitor the Buck converter output signal and provide a means of telling the system when the output voltage is within a certain operating range. Power Good can be used for system initialization, fault detection or start-up sequence.

Over Current Protection:

All Richtek Buck converters have Over Current Protection (OCP). When the inductor current exceeds the OCP level, the converter duty-cycle is limited. Further load increase will result in output voltage drop. However, there are different ways how the system behaves in overload condition:

- **Latch mode OCP:** When during overload the output voltage drops below the Under Voltage Protection (UVP) point, the system shuts down and latches. The converter needs to be re-enabled or cycle the input voltage for restart. This protection ensures zero power after overload, but does not have auto restart.
- **Hiccup mode OCP:** When during overload the output voltage drops below the UVP point, the system shuts down and initiates a restart with soft-start. Continuous overload will show continuous shut-down/restart cycle or hiccup mode. The advantage of hiccup mode is low average overload current, and guarantees auto restart after the overload is removed.
- **Non UVP:** During overload the output voltage drops, but there is no UVP action. The system continues to run at OCP current level during overload. The output voltage recovers immediately after the overload is removed. But the continuous OCP current level can lead to increased temperature in longer term overload conditions.

IC package selection considerations

Richtek Buck converters are available in many types of packages: from tiny CSP 1.3x2.1mm to cost effective TSOT-23-6 to larger TSSOP-14 thermally enhanced package.



Figure 10. Various IC packages used in Richtek Buck converters

Which IC package is most suitable for your application depends on a number of factors:



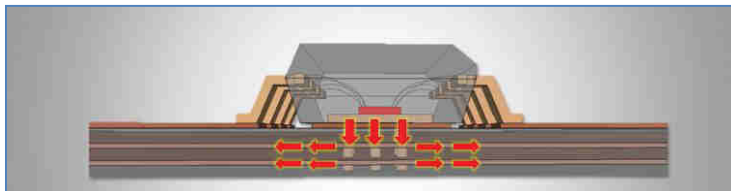
In applications that are extremely limited in height and PCB space (i.e. mobile phones and tablet PCs or other small portable devices) you will most likely select CSP packages. For these packages, multi-layer PCB layouts are required, and they need more precise placement and well controlled soldering process.



SOP-8 (exposed pad) and DFN2x2 and DFN3x3 packages are often used in Buck converters: Their pin count ranges from 6 ~ 12 pins for extra functionality, and they offer good thermal performance due to exposed thermal pad. They are cost effective, making them a popular choice for many applications. It is possible to use these parts in single sided layout, but for better thermal and electrical performance multi-layer PCB layouts are recommended.



Larger packages like TSSOP-14 or WDFN-14L 4x3 have larger thermal pads, which allow them to dissipate more power. It is important to connect the thermal pad to large PCB copper area, and use vias to inner layers to enhance the PCB cooling properties.



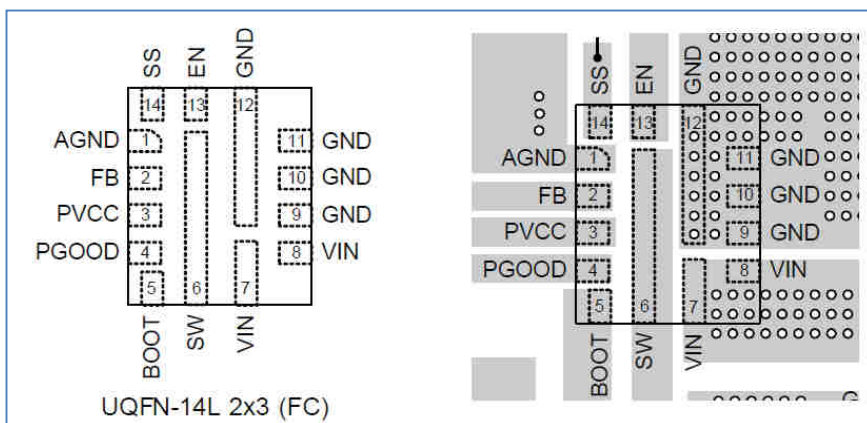
For lowest cost solutions, TSOT-23-6 and SOT-23-8 packages are a good choice. The 6-pin packages are sufficient for the basic Buck converter, while the 8-pin packages offer some extra functionality like soft-start or Power good. These packages have no thermal pad, so most of the IC heat dissipation must be removed through thermal flow via the package pins to the PCB copper. There are two different die assembly structures: traditional wire-bonding and flip-chip. The key advantages of a flip-chip package are better electrical performance and improved thermal capabilities compared to conventional wire-bonded products

Overview for conventional wire-bond vs. flip-chip on lead in TSOT-23-6 package:

Wire bonding:	Flip-Chip:
<p>The silicon die is glued to the center (GND) lead, and the die electrical connections are wired to the lead frame pins via bonding wires, which are typically 25-38um gold or copper wires.</p>	<p>The topside of silicon die is mounted via pillar bonding to the lead frame providing both the thermal and electrical connections directly from silicon die to the lead frame.</p>
Electrical performance differences:	
<p>The thin wires add resistance, inductance and stray capacitance to critical circuit nodes, which reduces the performance of high frequency switching converters.</p>	<p>The short interconnect length of pillar bonding delivers significantly less resistance, inductance and stray capacitance, which minimizing I²R and switching losses while reducing waste heat.</p>
Thermal performance differences:	
<p>The bonding wires are poor heat conductors so most of the potential heat transfer of the pins is lost. Heat transfer is mostly from the back side of the die through adhesive to the center ground pin, causing a hot spot on the center pin.</p>	<p>All pins are acting as small heat sinks and can be used for efficient cooling, so there is more heat transfer from package to PCB, resulting in lower die temperature.</p>



Buck converters with higher current capabilities ($\geq 6A$) often make use of flip-chip technology as well, to avoid the extra resistance of the bonding wires. These parts make use of UQFN packages with special lead frames for optimal connection to the silicon die in order to minimize the total $R_{DS(ON)}$. For optimal package cooling, it is key that the PCB layout has sufficient copper to the IC pin connections, with thermal vias to inner layers for increasing the heat-sinking effect of the PCB.



In Richtek datasheets, flip-chip packages have a designator "F" at the end of the full part-number.

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