Comparing the Boundary and Discontinuous Conduction Modes in Flyback Converters

Abstract

Embark on an application note journey and delve into the boundary conduction mode (BCM) and discontinuous conduction mode (DCM) within flyback converters. This application note provides perspective on the differences between these modes, while also shedding light on applications that can reap the rewards from each. Theoretical concepts come to life through bench validation using the *LT8301* (BCM) and *MAX17691* (DCM) flyback converters, comparing efficiencies, output ripple, thermal management, and EMI behavior. The goal is to provide insights to leverage BCM and DCM for various applications.

Introduction

Flyback DC-DC converters are essential components in a wide range of low-power applications, warranted by their cost-effectiveness and galvanic isolation capabilities. Within the portfolio of switching converters, there are three primary operational modes: boundary conduction mode (BCM), discontinuous conduction mode (DCM), and continuous conduction mode (CCM). This examination hones in on the intricacies of BCM and DCM, offering a comparative analysis of the two modes, that spans theoretical foundations to practical bench validation.

Beginning with an overview of flyback operation, consider the critical elements at play: the transformer, complemented by MOSFETs or diodes, a controller, and capacitors. **Figure 1** is a basic flyback converter serving as a visual aid, guiding through operation. The transformer, acting as an energy hub, fulfills roles encompassing energy storage, isolation, and voltage transformation. Orchestrated by the controller's commands, the switch controls the flow of current into the primary winding. When open, energy flows into the primary winding of the transformer. As the switch closes, energy transfers to the secondary output winding, where the capacitor filters the resulting output. Thus, creating a voltage change while remaining isolated from the input.

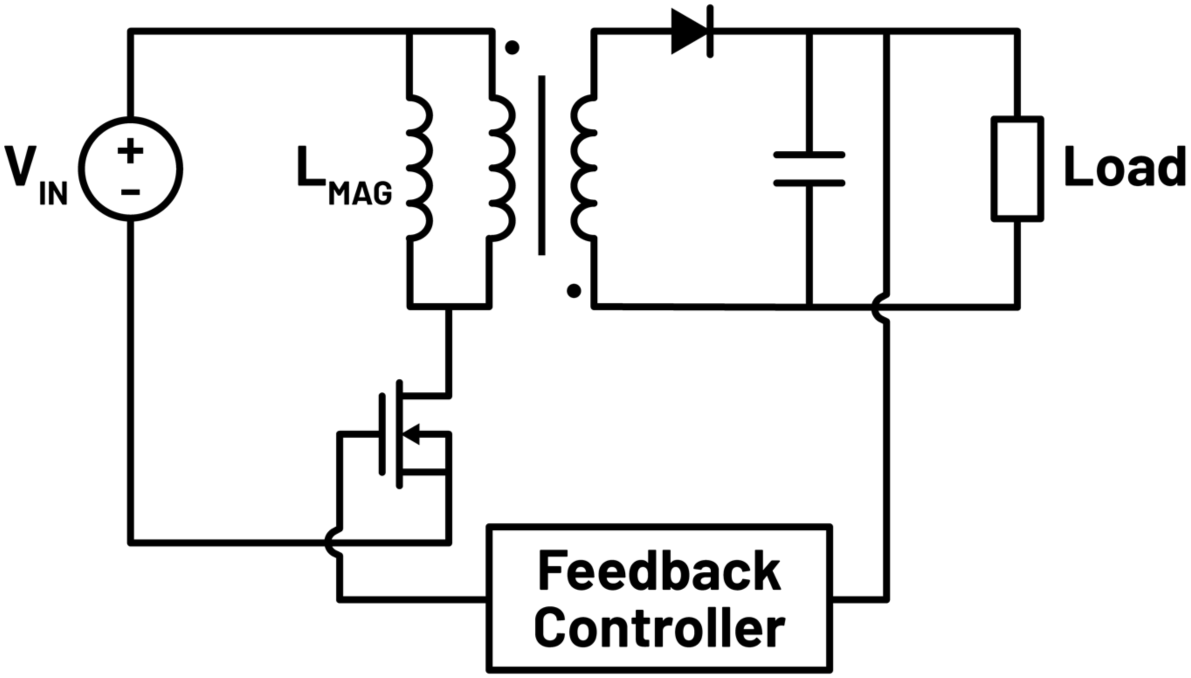


Figure 1. Circuit schematic of a basic flyback converter.

CCM is an operating mode where the current across the secondary winding of the transformer never reaches zero. This means that at any given time the secondary always has current flowing through. DCM is the opposite, where the current drops to zero every switching cycle for a certain amount of time. Figure 2 and Figure 3 showcase the current waveforms across the primary and secondary of the transformer as well as the voltage waveform of the MOSFET drain to source voltage. Figure 2 is under DCM while Figure 3 is under CCM.

For more detail about CCM and DCM operations as well as how to select a transformer for a flyback converter, see this Coilcraft article: **A Guide to Flyback Transformers**.

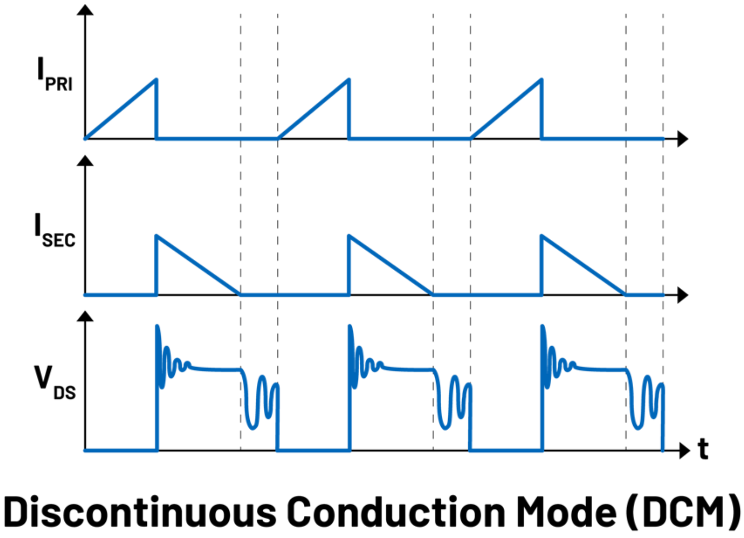


Figure 2. DCM current and voltage waveforms.

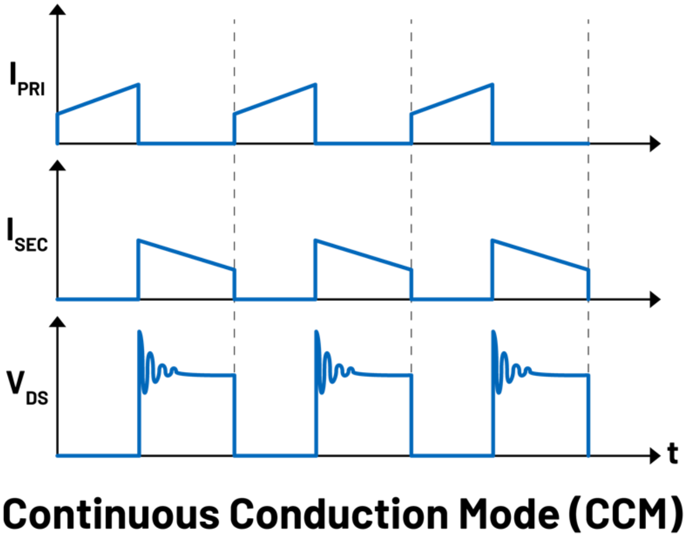


Figure 3. CCM current and voltage waveforms.

Theoretical Differences

Now that a flyback converter is defined and it is known how DCM operates, what are some key differences when discussing BCM? What are the features and how might they benefit an application? From a high level, BCM and DCM operate in almost the same fashion. Since the current in the secondary winding drops to zero while under DCM, does the same happen in BCM? The answer is yes. BCM also drops the secondary current to zero. However, the difference is that as soon as the secondary winding drops to no current, the controller switches the MOSFET on so that there is no dead-time in the switching cycle. This causes the converter to operate in variable frequencies. That means that BCM is “smart” in the sense that it actively adjusts the switching frequency as the load changes. BCM operates at the boundary of CCM and DCM, which takes advantages from both modes. To learn more about BCM and how to design a converter that uses this mode, read the **Isolated Power Supplies Made Easy** application note that features the **LT3748**. Figure 4 shows the idealized current and MOSFET voltage waveforms of BCM operation.

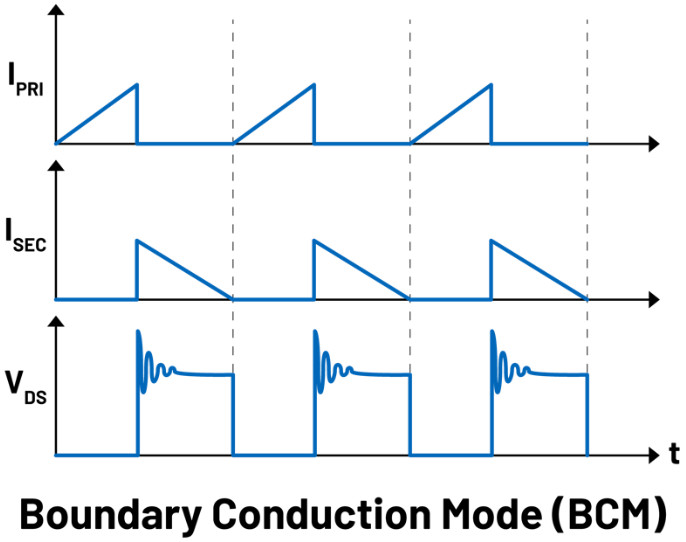


Figure 4. BCM current and voltage waveforms.

A Closer Look at the LT8301 and MAX17691

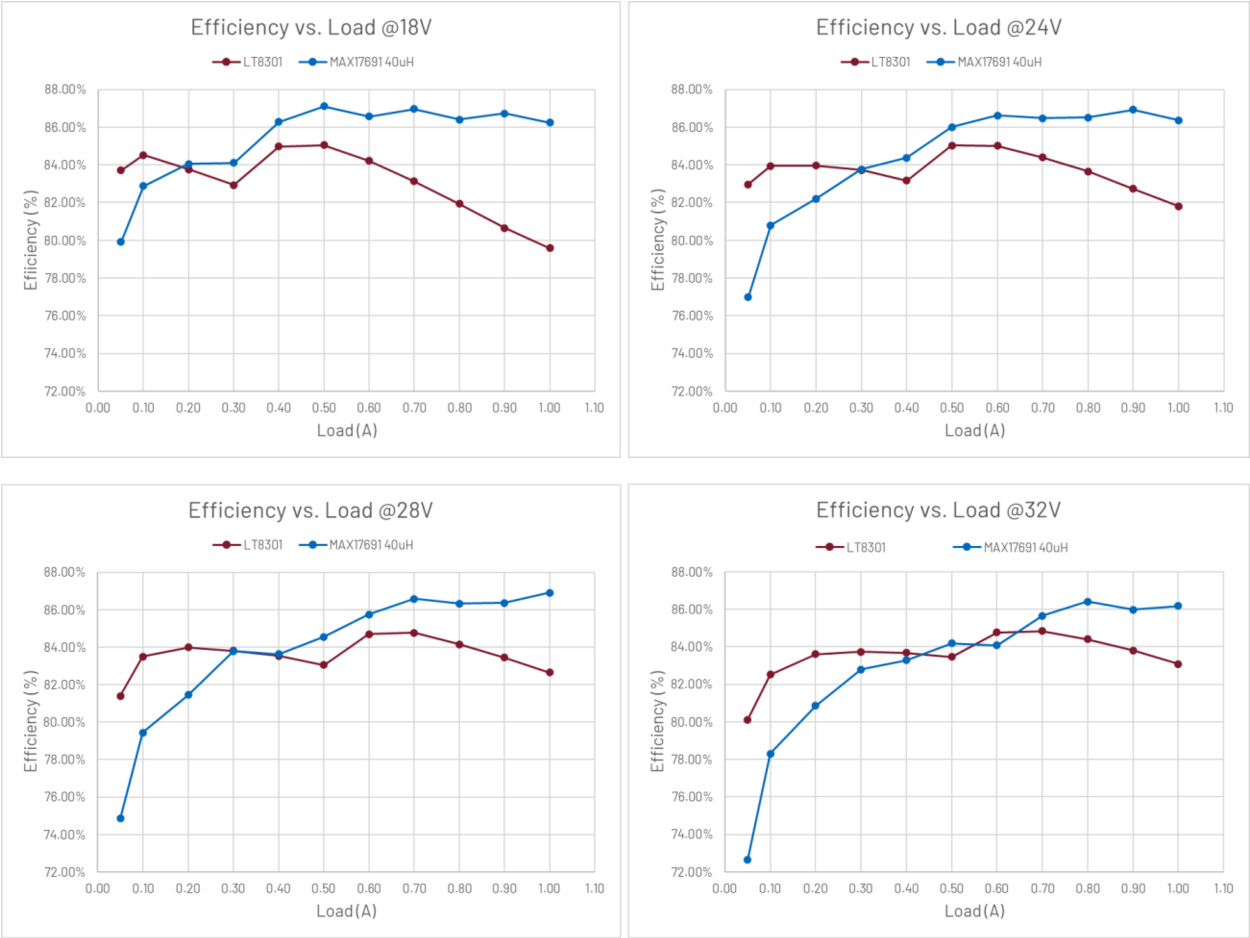
In the pursuit of understanding the differences between boundary conduction mode (BCM) and discontinuous conduction mode (DCM) in flyback converters, the LT8301 and MAX17691 integrated circuits (IC) were examined. These ICs respectively represent BCM and DCM. Let us delve into their evaluation (EV) boards to explore how to ensure a fair comparison and uncover the testing approach.

Despite their differing operational modes, both EV boards share similar structural elements, allowing for a comparison free from structural biases. To further solidify the fairness of the comparison, one adjustment was made for experimentation. The 40μH transformer from the LT8301 was used for both boards, with the 22μH transformer from the MAX17691 being removed and disregarded. Calculations from the MAX17691 data sheet verify that a 40μH transformer is appropriate to use instead of the 22μH. This alteration enabled more accurate evaluation and comparison of their performance attributes.

The testing encompassed a range of scenarios, with the EV boards tested at different input voltages: 18V, 24V, 28V, and 32V. Additionally, tests were conducted across various load levels, spanning from no load to full load (0A to 1A) The EV boards for the LT8301 and MAX17691 were designed for slightly different input ranges. So, the tests were conducted at shared values that both could achieve. The LT8301 operates from 10V to 32V input, whereas the MAX17691 functions from 18V to 36V. Input and output voltage and current were measured to calculate efficiency. Output ripple was also measured. This comprehensive testing approach resulted insights into their performance across diverse operating conditions. The data obtained from these tests facilitated an analysis of efficiency, output ripple, and temperature behavior.

Converter Efficiency

Efficiency is a paramount consideration in the realm of flyback converters and plays a pivotal role in determining their suitability for specific applications. Beyond just the numbers, efficiency impacts the overall environmental sustainability of the complete system. Better efficiency reduces power losses, resulting in lower energy consumption. Further, flyback converters often feed many loads on the other side of the isolation barrier, meaning the efficiency impacts a large portion of the system. On diving into the LT8301 and MAX17691, the impact of these IC's power optimization capabilities is illuminated. Now that the boards are selected and component swaps are complete, let us look at the efficiency graphs (Figure 5) that were obtained. In the investigation of the LT8301 and MAX17691 EV boards, their efficiency profiles were analyzed across varying load conditions at four different input voltages: 18V, 24V, 28V, and 32V. The results provide insights into their performance and the applications they may be best suited for.



Efficiency vs. Load @18V

Efficiency vs. Load @24V

Efficiency vs. Load @28V

Efficiency vs. Load @32V

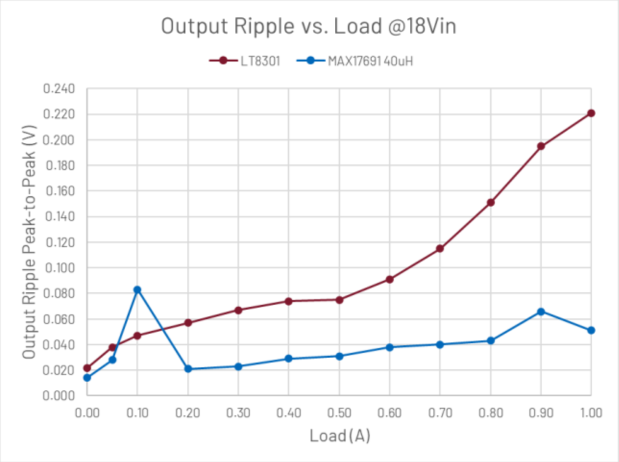
Figure 5. Line charts of LT8301 and MAX17691's efficiency measurements.

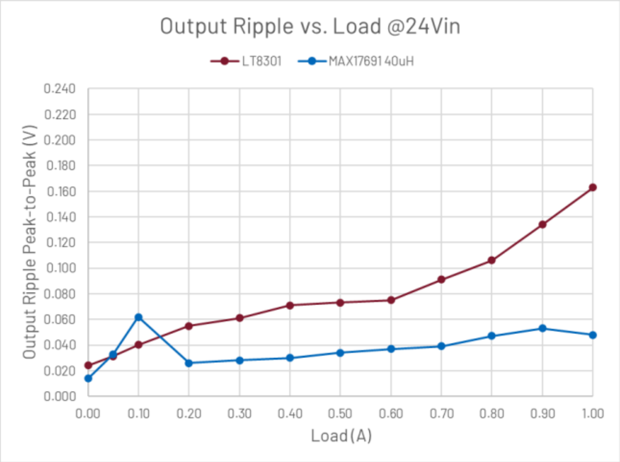
The LT8301 exhibited a tighter efficiency spread from 0A to 1A on average. Its efficiency ranged from a minimum of 80% to a maximum of 85%. As shown on the graphs, as the load is increased, frequency changes internally, which self corrects its efficiency as it starts to dwindle around 0.3A to 0.5A. That is, BCM is hard at work to keep efficiency as stable as it can get. This trend suggests that BCM is exceptionally well-suited for applications with dynamic load conditions. In electric vehicles (EVs), for example, where power must efficiently go from a high-voltage (HV) battery to the low-voltage (LV) battery, be it from a HV buck converter that then passes it to the flyback for isolation, BCM demonstrates its adaptability. In a car, there are large variations in load within the cabin of the vehicle. All the electronics that must be powered, like the speakers and AC fan speed, can be turned off or set to full power. The flyback converter’s ability to maintain high efficiency across a wide range of loads is crucial in scenarios where power demands fluctuate dramatically. In the realm of industrial automation, where machines move with varying speeds and motions, BCM also takes a stand to perform. Industrial automation encompasses an array of applications, including robotics, conveyor systems, and motion control systems, where precision and synchronization are paramount. In such settings, machines must move, stop, and adjust their motions non-stop. A BCM flyback converter is the optimal choice for situations like these.

The MAX17691, in contrast, presented an efficiency profile with a broader range from 0A to 1A, spanning from a minimum of approximately 73% to a maximum of 87%, generally increasing with increased current. This characteristic aligns DCM with applications that run at full load, without significant variation, such as industrial automation and process control. In settings involving heavy-duty processes that operate near maximum load capacities around the clock, DCM provides consistently high efficiency at heavy loads making it an ideal choice. Understanding the efficiency characteristics for both BCM and DCM paves the way for selecting the most suitable converter for specific application needs.

Converter Output Ripple

The analysis of output voltage ripple for the LT8301 and MAX17691 has unveiled noteworthy distinctions in their performance, shedding further light on their applicability across diverse industries. In Figure 6, the graphs show output ripple as load and voltages increase, for the same conditions as the previous efficiency testing scenarios. Notably, the MAX17691 demonstrates great output ripple characteristics across a spectrum of input voltages and load conditions, positioning it as a strong contender for applications where stability and precision are paramount.





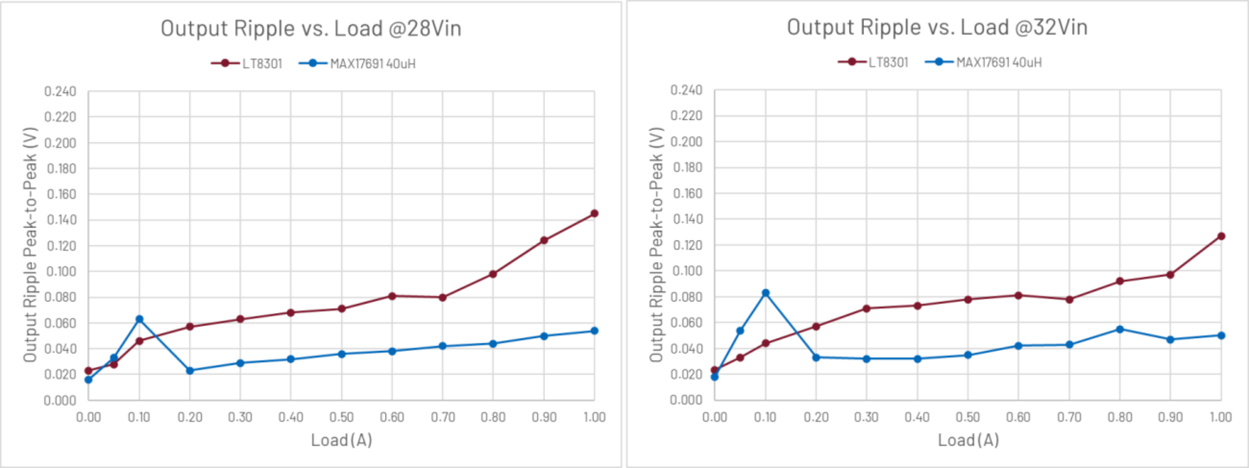


Figure 6. Line charts of LT8301 and MAX17691's output ripple.

In the realm of medical equipment, where precision and stability are non-negotiable, DCM's exceptional output ripple characteristics take center stage. The fine-tuning and stability of medical devices heavily rely on a consistent power supply. DCM's ability to maintain low output voltage ripple ensures that sensitive medical instruments can operate with the precision they demand. Whether it is diagnostic equipment, imaging devices, or life-saving monitoring systems, DCM's reliability in delivering clean power aligns seamlessly with the stringent requirements of the medical field.

Robust signal integrity is paramount in modern communication systems. Any wavering in power delivery can compromise the performance of vital communication infrastructure. Here, DCM's output ripple characteristics ensures uninterrupted and high-quality data transmission. In communication networks, where data flows continuously and without interruption, DCM's ability to provide clean and stable power reduces the risk of signal degradation or failures. This resilience makes it an apt choice to bolster the reliability of communication systems. The choice between BCM and DCM ultimately hinges on the specific requirements of the application.

Converter Thermal Captures

Understanding the thermal behavior of converters in demanding applications is instrumental in assessing their suitability and reliability. In the investigation, the thermal performance of the LT8301 and MAX17691 across a range of conditions were examined. The results not only shed light on their thermal profiles but also reveal how DCM's operating temperatures can make it an asset in the demanding landscape of industrial automation.

When subjected to a 1A load at 18V, BCM exhibited peak temperatures of 40.35°C on the transformer and 43.37°C on the chip. In comparison, DCM displayed temperatures of 35.15°C on the transformer and 33.42°C on the chip under the same test conditions. A similar trend persisted at a 32V 1A load, where BCM recorded peak temperatures of 37.8°C on the transformer and 38.18°C on the chip, while DCM maintained significantly lower temperatures of 35.5°C on the transformer and 33.67°C on the chip. The temperature differences are at the extreme a 10°C difference on the chip at 18V and a low of about 2°C on the transformer at 32V for BCM and DCM. The thermal captures that underpin the findings were obtained from a Fluke Ti401P thermal camera. The testing procedure allowed the converters to operate for 20 minutes as a stabilization period before capturing the images. The converters were subjected to full load (1A) testing under 18V and 32V. These thermal captures are shown in Figure 7 and Figure 8.

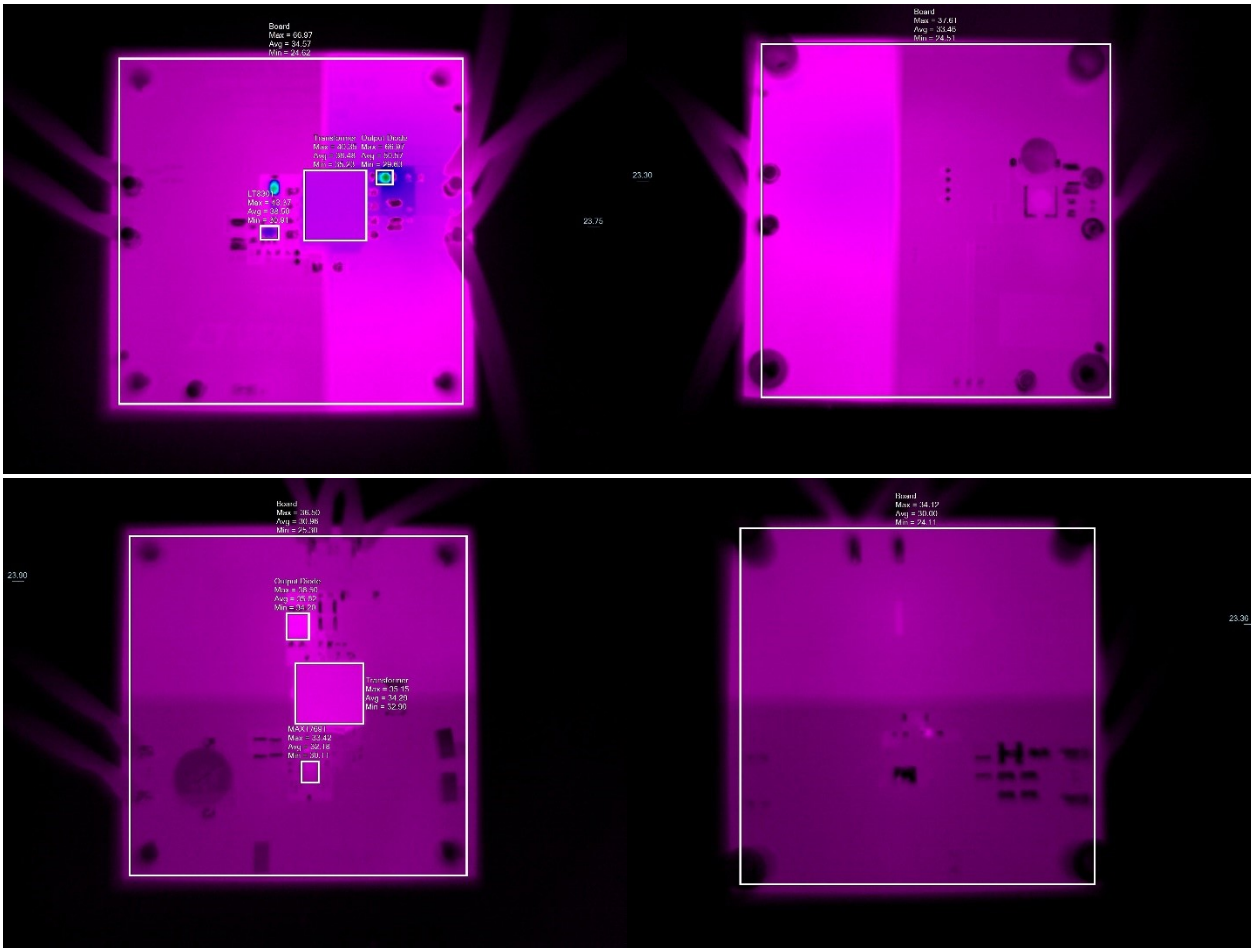


Figure 7. Thermals of the LT8301 (top) and MAX17691 (bottom) EV boards at 18V 1A load.

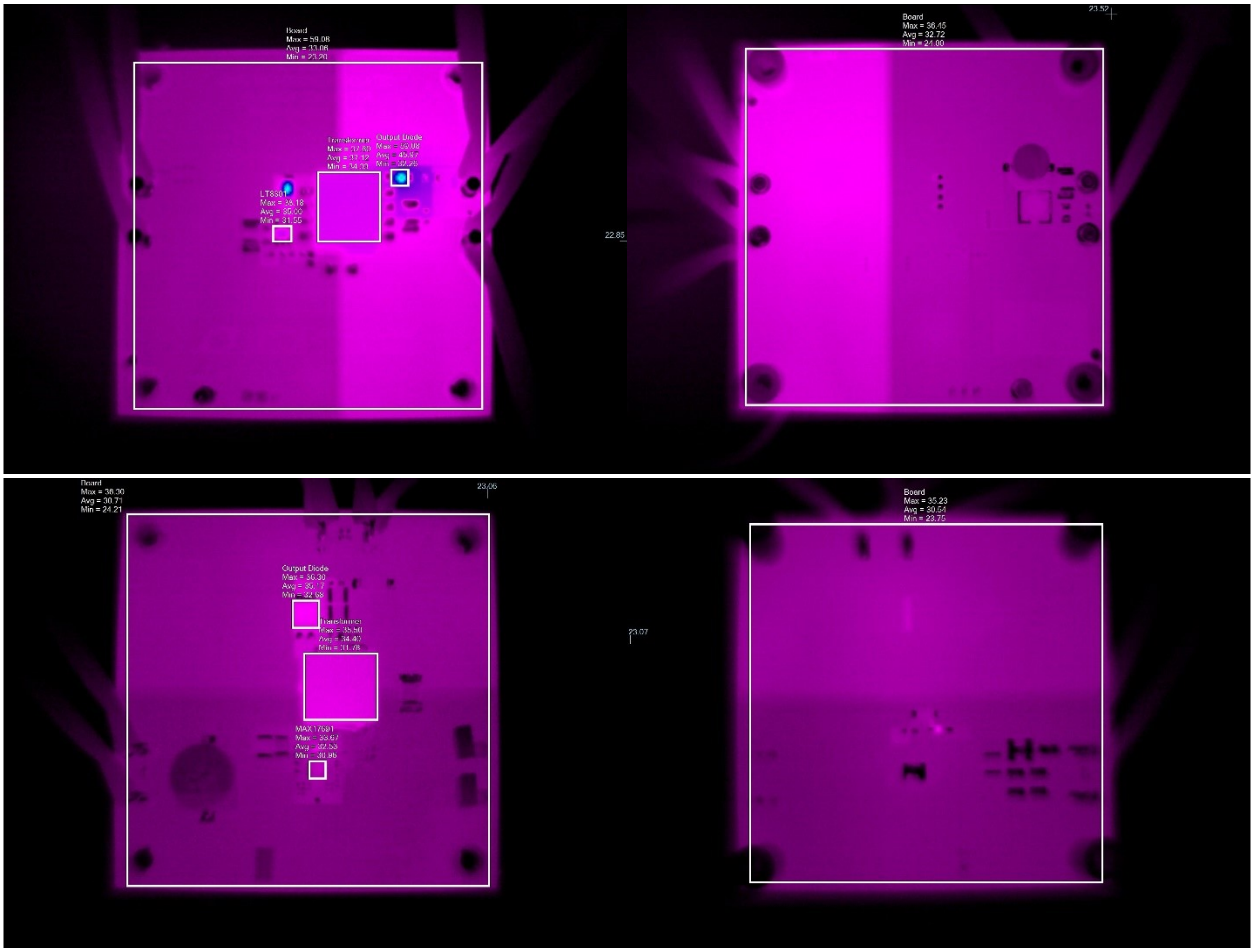


Figure 8. Thermals of the LT8301 (top) and MAX17691 (bottom) EV boards at 32V 1A load.

These findings underscore DCM's abilities in environments with high temperatures and limited cooling mechanisms (conditions frequently encountered in the industrial automation sector). Industrial machinery, often devoid of fans, generates substantial heat during operation. In this context, DCM's thermal ability translates into several benefits. It not only contributes to effective heat management within these machines but also enhances their overall operational reliability. DCM's capacity to function reliably and efficiently in high-temperature settings is important for industries where uninterrupted performance is critical, making it an ideal choice for industrial automation applications.

Importantly, it is crucial to emphasize that both BCM and DCM have their merits and can find a place in the industrial automation landscape. BCM's robust performance should not be overlooked; it remains a viable choice, especially in scenarios where specific load or efficiency requirements dictate its use. Ultimately, the selection between the two converters hinges on the unique needs of the application. The goal is to empower engineers with the knowledge to make informed choices, ensuring that both BCM and DCM can thrive in the domains of industrial automation, each excelling to meet specific demands.

Conclusion

In the vast landscape of flyback converters, the application note has reached the destination to unravel the nuances between discontinuous conduction mode (DCM) and boundary conduction mode (BCM). However, it is essential to underscore that these are not the sole modes to consider when selecting a topology. The world of flyback converters offers a diverse palette of operational modes, each uniquely suited to specific applications.

One critical aspect that emerges from the exploration is the inherent advantage of DCM and BCM, both of which require smaller transformers than CCM. This characteristic enables them to thrive in applications where space constraints are a concern. Moreover, let us not forget the fundamental reasons why flyback converters are so great. Offering galvanic isolation, accommodating multiple outputs, and delivering efficiency are their hallmarks, making them indispensable across a broad spectrum of industries.

The LT8301 (BCM), as learned, finds its forte in the realms of automotive and motion control industrial automation. Its stable efficiency across varying load conditions from low to high makes it a reliable choice in scenarios where adaptability is key.

On the other hand, the MAX17691 (DCM) shines in process control industrial automation, communications infrastructure, and medical applications. Its output ripple characteristics and thermal performance position it as an asset in environments characterized by high temperatures and demanding signal integrity requirements.

In the end, the choice between BCM and DCM is not about one being superior to the other; it is about understanding the unique needs of the application at hand. Engineers are encouraged to weigh factors such as efficiency, output ripple, and thermal behavior when making their decision, ensuring that both converters are equipped to excel. Both converters stand ready to meet any needs, each with its own strengths and capabilities, awaiting an application's unique requirements to shine.