AN5960

Application note

The isobuck-boost topology enhances performances of A/L6986I and A/L6983I

Introduction

The A/L6986I and A/L6983I are buck converters dedicated to isolated applications. They implement an isolated buck topology (isobuck), where the isolated output regulation relies on the primary output accurate regulation and the transformer selection. Since the primary circuit is a buck converter, the input voltage must be higher than the primary output voltage. In addition, for a correct isobuck operation, the duty cycle is required to be below 70%.

Nevertheless, in some conditions there is the need for higher duty cycle operation:

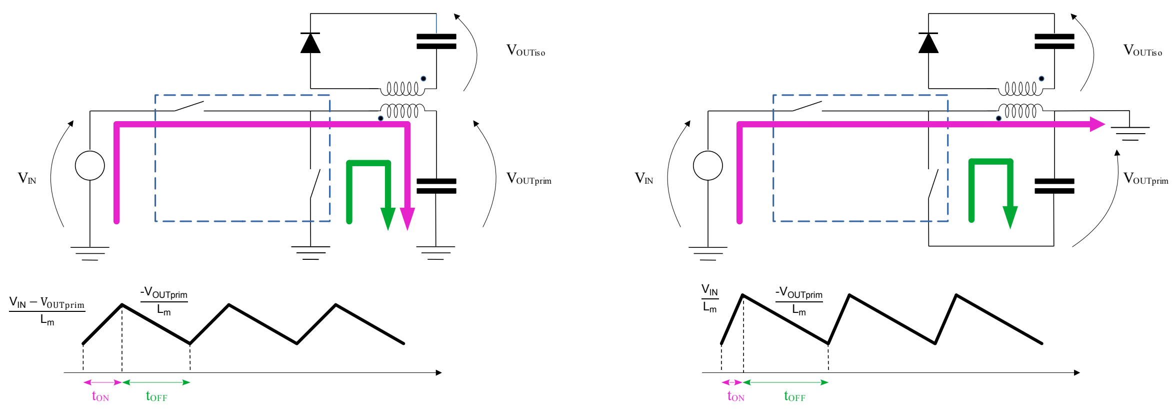
- Lower input voltage (for example, to match the typical car battery voltage range)
- Higher primary output voltage, necessary in some cases to reduce the turn ratio of the transformer

Under these circumstances, the architecture helps allowing a better exploitation of the input voltage range and the current capability of the A/L6986I and A/L6983I.

The constraint of the duty cycle, whose definition changes (see figure below), is less stringent in the isobuck-boost and enables to manage wider input and output voltage ranges.

This document describes the limitations and the impact of high duty cycle operation for the isobuck and introduces the topology with its advantages as well as the main constraints, providing examples and comparative performance results.

Figure 1. Current flows and duty cycle definition for the isobuck (left) and isobuck-boost (right)



$$D = \frac{V_{OUTprim}}{V_{IN}}$$

$$D = \frac{V_{OUTprim}}{V_{IN} + |V_{OUTprim}|}$$

1 Duty cycle influence in the isobuck

One of the key parameters of the isobuck is the duty cycle. Normally, extreme duty cycle operation is not recommended.

A very low duty cycle poses a possible problem as it might conflict with the minimum on-time of the device (for example, t_{ON_min} is around 330 ns typ. for A/L6986I, 390 ns typ. for L6983I). A t_{ON} shorter than the minimum value causes the device to skip cycles to keep the regulation.

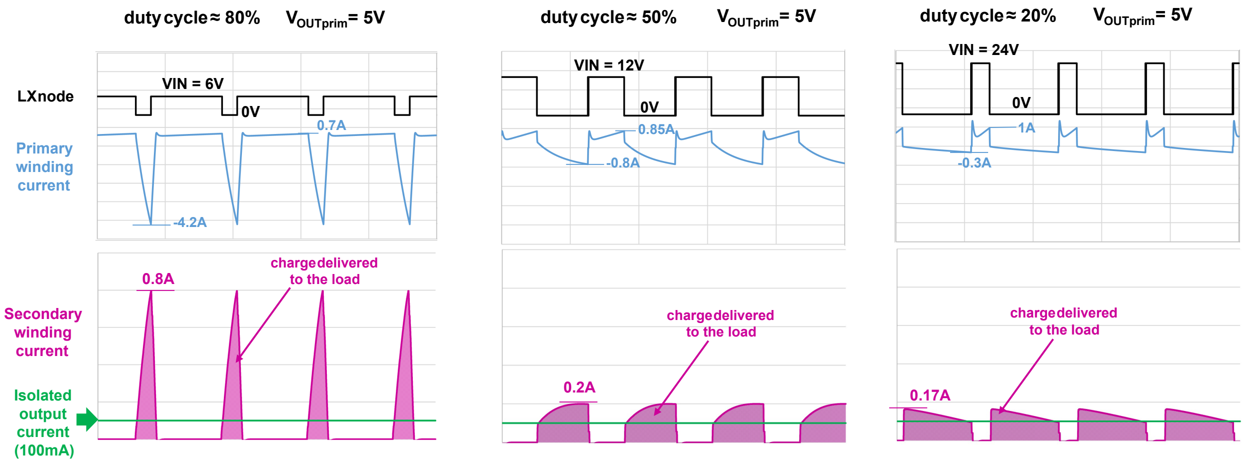
The duty cycle must be hence above a minimum value, which depends on the switching frequency:

$$D_{MIN} \geq f_{SW} \cdot t_{ON\_min} \quad (1)$$

Duty cycle higher than a certain value (70% as a rule of thumb) should also be avoided.

Figure 2 shows three different duty cycle conditions with equal delivered power to the isolated output.

Figure 2. Evolution of the shape of the primary and secondary winding currents according to different duty cycles (simulated curves for A/L6983I, $V_{OUTprim}$ = 5 V, N = 6, f_{SW} = 400 kHz)



Increasing the duty cycle leads to the following effects:

- Keeping the same load conditions at the isolated output, a reduced off-time means a higher current peak in the secondary winding
- A higher current peak in the secondary winding implies a more negative current peak in the primary winding, therefore reducing the margin from the reverse current limit. This translates into a limited deliverable power
- High peak impulsive current in the secondary winding impact on the losses. The load regulation is significantly affected, as shown in Figure 3.

Other than the considerations regarding the minimum on-time, lower duty cycles have a slight influence on the positive peak of the primary winding current, according to the following equation:

$$I_{PRIM\_PEAK} = N \cdot I_{OUTiso} + \frac{(V_{IN} - V_{OUTprim}) \cdot D}{L_m \cdot F_{SW}} \quad (2)$$

A good compromise is trying to operate at a duty cycle around 50%.

Figure 3. Load regulation at different input voltages. V_{OUT_prim} = 5.3 V, transformer ZB1175-AE (N = 1.58)

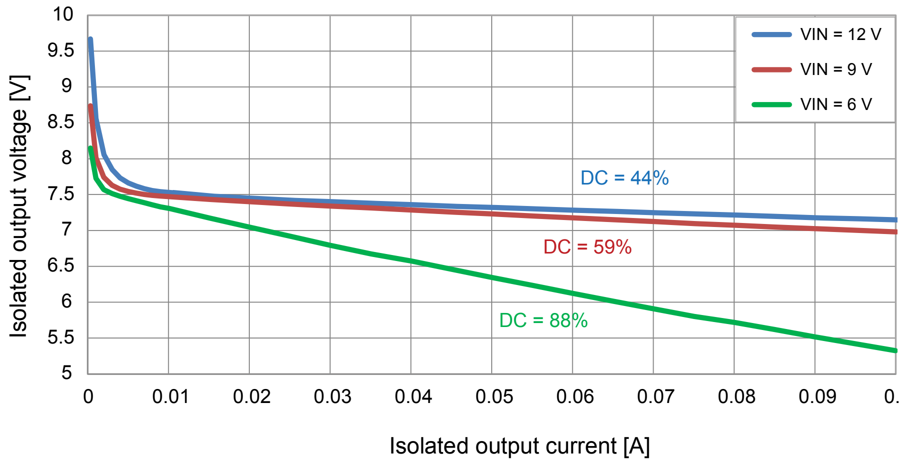
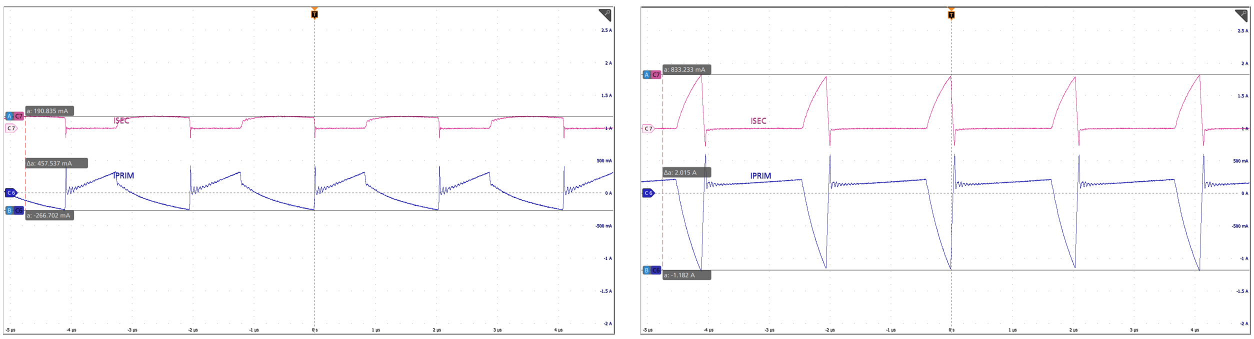


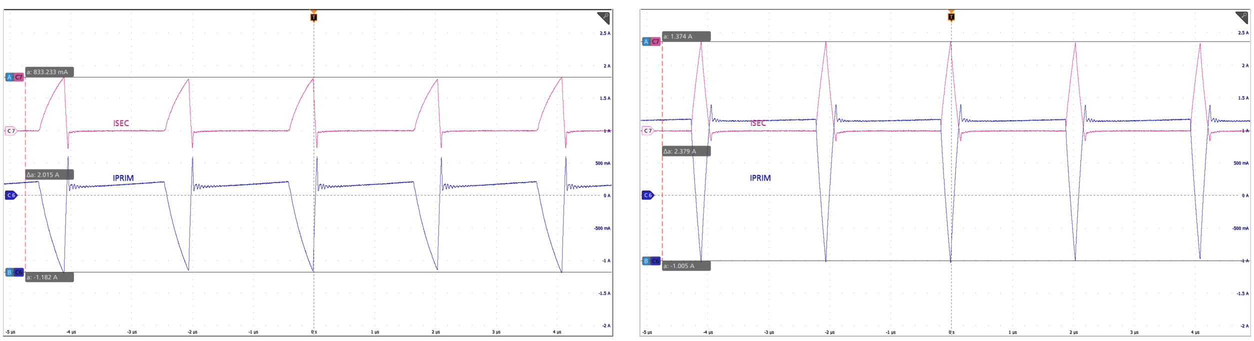
Figure 4 restates the effect of the duty cycle on the current peaks in a real measurement with A/L6986I. The image on the right (duty cycle 88%) shows that the current in the primary winding during the t_{OFF} is close to the reverse current limit (minimum value at ambient 1.285 A).

Figure 4. Peak currents in the primary winding (blue) and secondary winding (purple), with 100 mA load at the isolated output, at different duty cycles: 44% (left, V_{IN} = 12 V) and 88% (right, V_{IN} = 6 V). V_{OUT_prim} = 5.3 V



Typically, a possible workaround to increase the current capability would be to add a load at the primary not isolated output. This additional load would shift the average current (in the primary winding) up, so that a slightly higher margin from the reverse current limit is achieved (see Figure 5).

Figure 5. Comparison between solution with (right) and without (left) load applied (1 A) to the primary output



On the other hand, the isolated output is not always loaded in real applications and adding a dummy load represents a waste of energy that significantly affects efficiency. Moreover, under high duty cycle operation this additional load would be counterproductive. A load applied at the primary output would in fact force the loop to further increase the duty cycle, leading to an additional unfavorable impact on the isolated output load regulation.

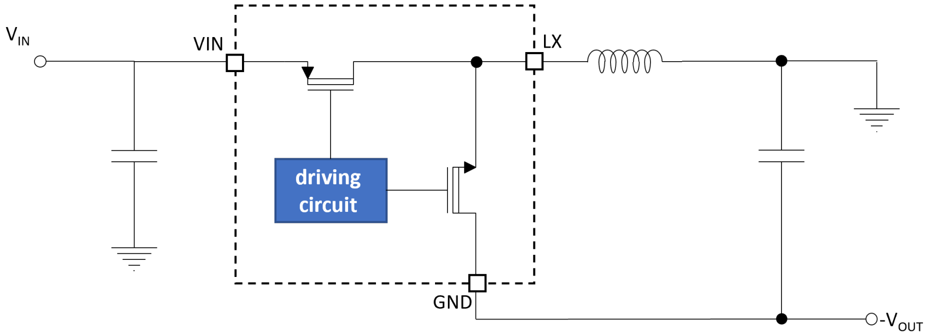
2 Using an inverting buck-boost at the primary side

From the previous section, the isobuck topology transfers the charge during the t_{OFF} (charge integrated over the period represents the output current). Consequently, short t_{OFF} operation (high duty cycle operation) becomes critical to deliver isolated output power and so a balanced duty cycle operation is recommended.

Figure 6 shows how to derive an inverting buck-boost topology from a buck converter with some minor schematic changes and adding a capacitor.

Hereafter it describes how the balanced duty cycle of this topology maximizes the isolated power delivery in application cases where the use of an isobuck turns out to be disadvantageous.

Figure 6. Basic schematic of an inverting buck-boost derived from a buck converter



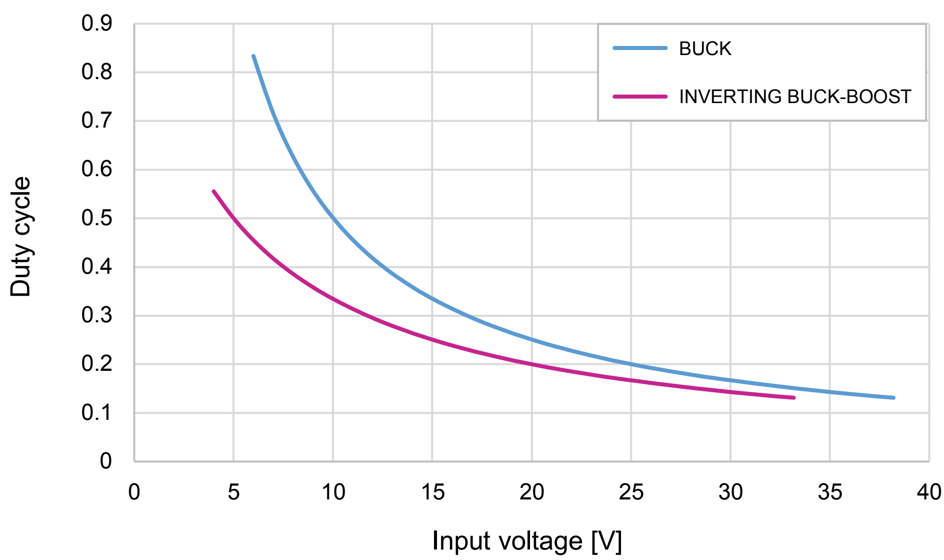
The definition of the duty cycle for the inverting buck-boost changes as follows:

$$D = \frac{|V_{OUT}|}{|V_{OUT}| + V_{IN}} \quad (3)$$

Figure 7 shows the comparison of the value of the duty cycle between a buck and an inverting buck-boost, keeping the output voltage equal (5 V). It highlights the dramatic reduction of the duty cycle especially at lower input voltages.

For example, in the application described in the previous section, with V_{IN} = 6 V and V_{OUT} = 5.3 V (actually -5.3 V in the case of inverting buck-boost), the duty cycle would be 30% instead of 88%.

Figure 7. Duty cycle vs. input voltage for a buck and for an inverting buck-boost



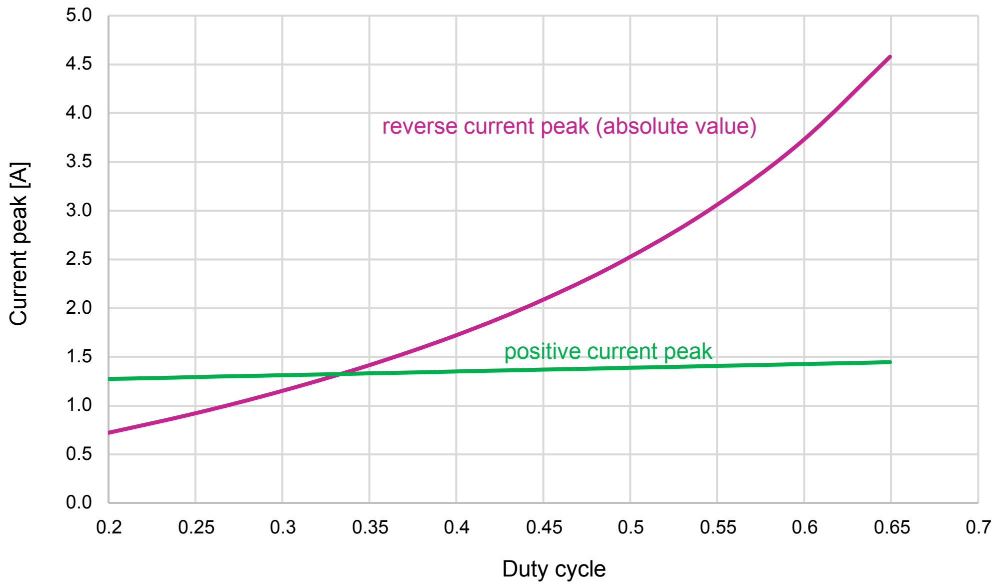
As shown on page 1, for not isolated architectures, the energy delivery to the load occurs during the whole period for a buck, whereas only during the t_{OFF} in an inverting buck-boost.

As far as the isolated architectures are concerned, the energy transfer to the load at the secondary side always takes place during the t_{OFF}, regardless of the implemented topology (isobuck or isobuck-boost). The advantage of reducing the t_{OFF} in the inverting buck-boost used as an isolated converter (isobuck-boost) is therefore evident: a longer period for transferring energy implies a lower current peak.

The current peak in the secondary winding is reflected to the primary winding, generating a negative peak. The isobucks are characterized by a so-called reverse current limit protection, which aims at limiting the negative current during the t_{OFF}. Limiting the negative current peak provides more margin from the current limit protection, leading to a higher deliverable power.

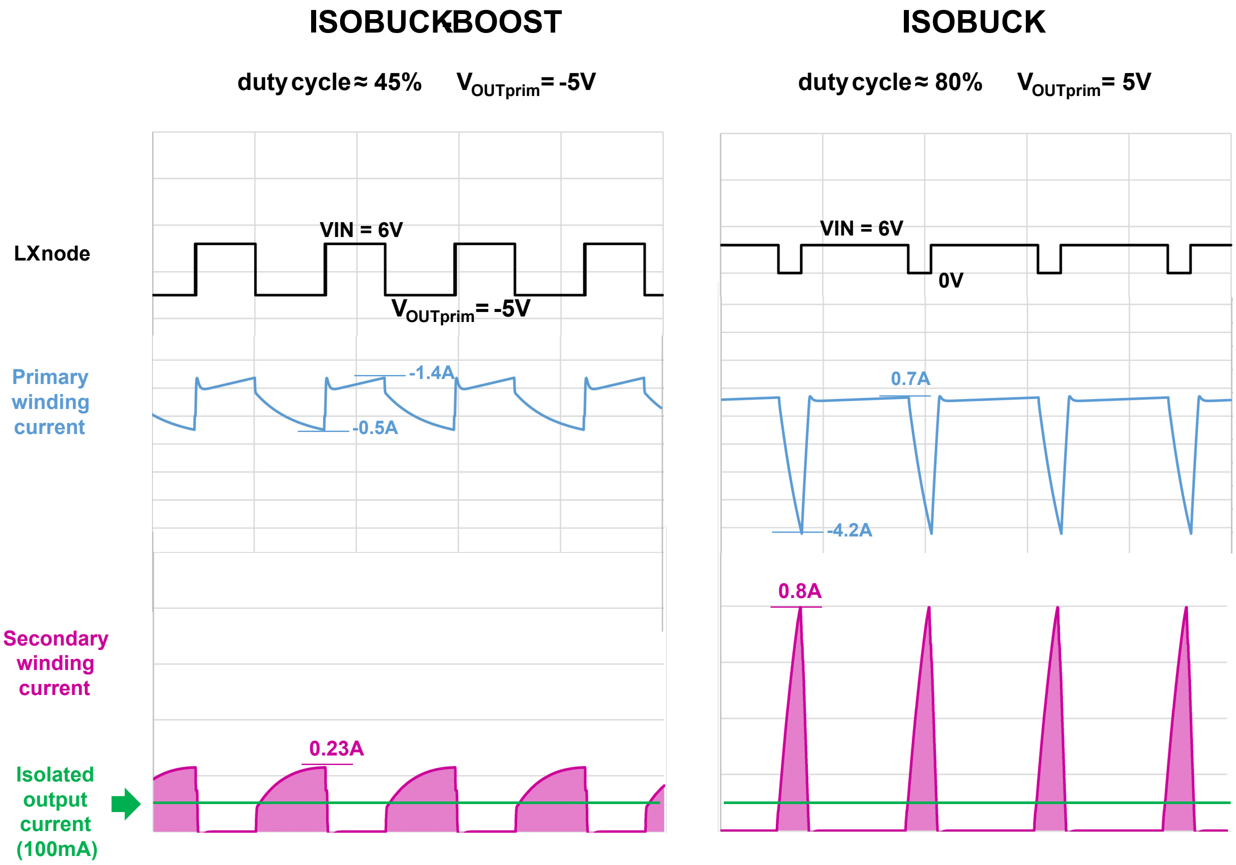
Figure 8 depicts the variation of the positive and negative current peaks with the duty cycle variation. While the positive peak is only slightly affected by the duty cycle, the negative peak steep increase further proves how convenient it is, in terms of deliverable power, to operate with low duty cycle.

Figure 8. Positive and negative current peaks vs. duty cycle, N = 4, I_{OUTiso} = 300 mA



The impact of using the isobuck-boost on the duty cycle and, consequently, on the current peak is summarized in Figure 9.

Figure 9. Comparison of the current waveforms between isobuck and isobuck-boost



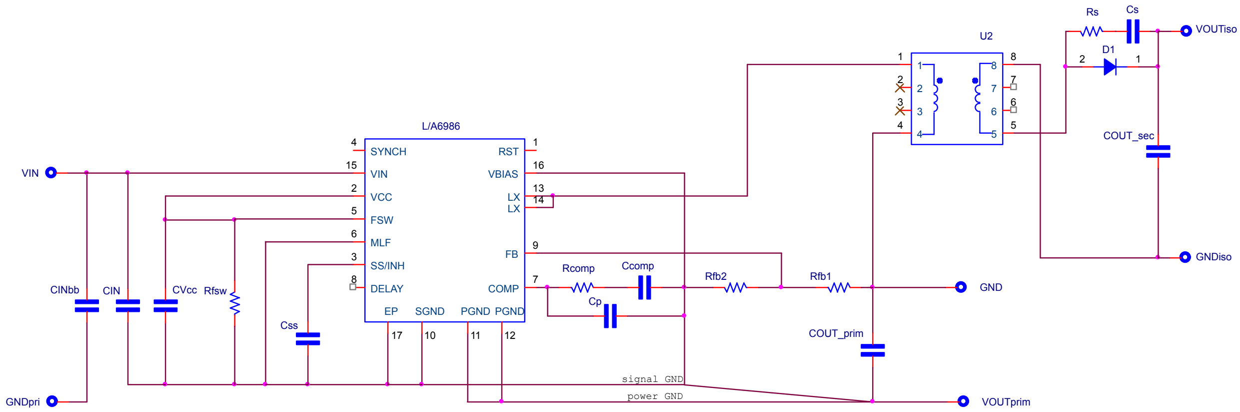
The known drawbacks for the inverting buck-boost are still valid for the isobuck-boost:

1. The input voltage range is reduced because the V_{IN} pin of the device is no longer subject to just V_{IN} but to $V_{IN}+|V_{OUT}|$.
2. Higher current in the winding and in the switches means higher power losses and lower efficiency.
3. The primary output voltage, sometimes used as auxiliary voltages in some applications, is in this case negative.

3 Isobuck-boost with A/L6986I

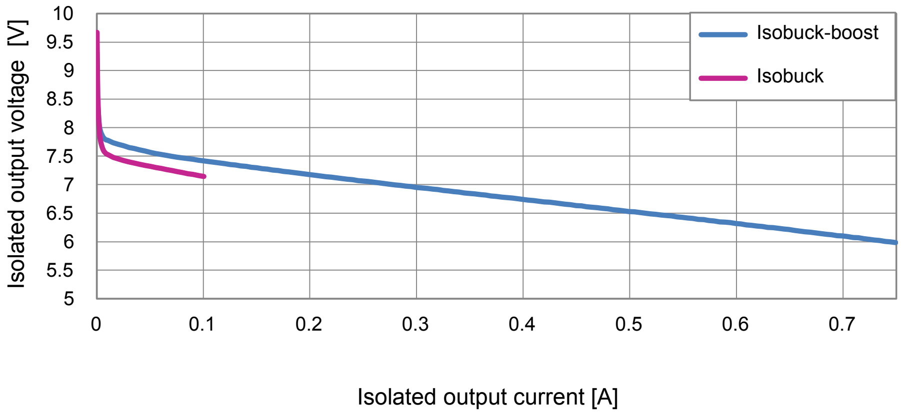
Figure 10 shows the schematic of the isobuck-boost solution with the A/L6986I.

Figure 10. Isobuck-boost schematic with A/L6986I



The significant improvement in terms of deliverable power is shown in Figure 11, where the load regulation performances of the isobuck and isobuck-boost under the same conditions (V_{IN} = 6 V, V_{OUT_prim} = 5.3 V, same transformer) are compared.

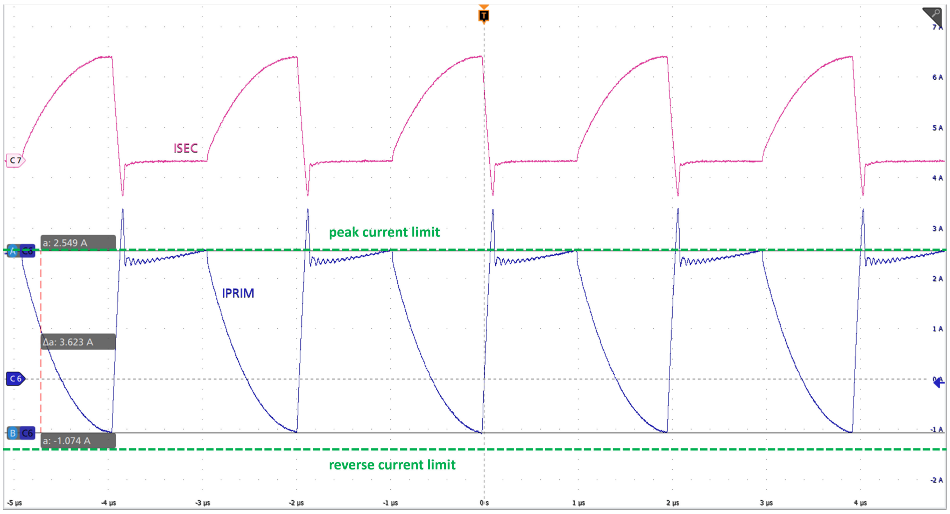
Figure 11. Load regulation comparison between isobuck and isobuck-boost



The maximum value of the output isolated current is defined differently for each solution, due to the mentioned shift upwards of the current in the primary winding:

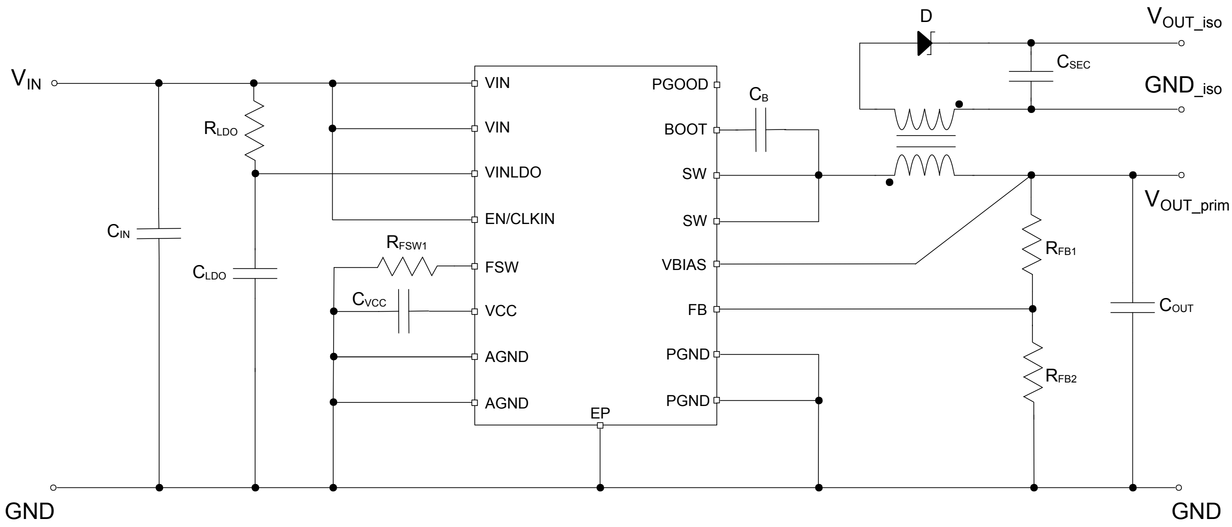
- For the isobuck, when the negative peak in the primary winding reaches the minimum value of the reverse current limit indicated in the datasheet (see Section 1, on the right)
- For the isobuck-boost, when the positive peak in the primary winding reaches the minimum value of the peak current protection indicated in the datasheet (see Figure 12)

Figure 12. Winding currents in the isobuck-boost with an isolated output current of 750 mA



4 Isobuck-boost with A/L6983I

Figure 13. **Isobuck-boost schematic with A/L6983I**



With minor changes, similar to the ones implemented for A/L6986I, the A/L6983I can also be turned into an isobuck-boost (see schematic in Figure 13).

The waveforms in Figure 14 compare the current in the primary winding using the isobuck and the isobuck-boost architectures.

While in the isobuck solution the current first exceeds the reverse current limit threshold (minimum value of the datasheet - 4 A), in the isobuck-boost the peak current limit is first exceeded (minimum value of the datasheet 4 A). Nevertheless, with the isobuck-boost a higher current (670 mA instead of 450 mA, with a higher isolated voltage too) can be delivered at the isolated output due to some advantages obtained through this architecture.

Since it is no longer mandatory to comply with the requirement $V_{IN} < V_{OUTprim}$, a different regulated primary voltage (-12 V instead of 5 V) can be adjusted, leading to a lower turn ratio, which consequently implies a lower secondary current peak (reflected as a lower negative peak in the primary winding). This explains why the reverse current limit is no longer exceeded, instead the peak current represents the main constraint.

Figure 14. **Primary winding current waveforms for isobuck solution (left) and for isobuck-boost solution (right), at the maximum isolated output current**

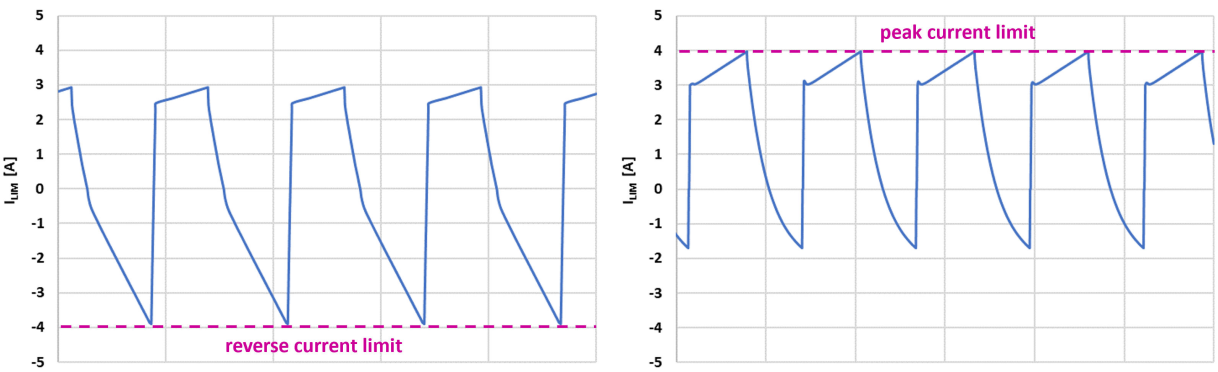


Table 1. Summary of maximum isolated output current, voltage, and power for isobuck and isobuck-boost solution

Solution	V_{OUT_iso} max [V]	I_{OUT_iso} max [mA]	Max isolated power [W]
Isobuck	22.3	450	10
Isobuck-boost	26.6	670	17.8

5 Application examples

5.1 Low input voltage

Another advantage in implementing an inverting buck-boost at the primary side is the inherent capability of any buck-boost to also manage input voltage lower than the output.

When the input voltage is very low, the isobuck still remains an option. But some constraints make this application challenging:

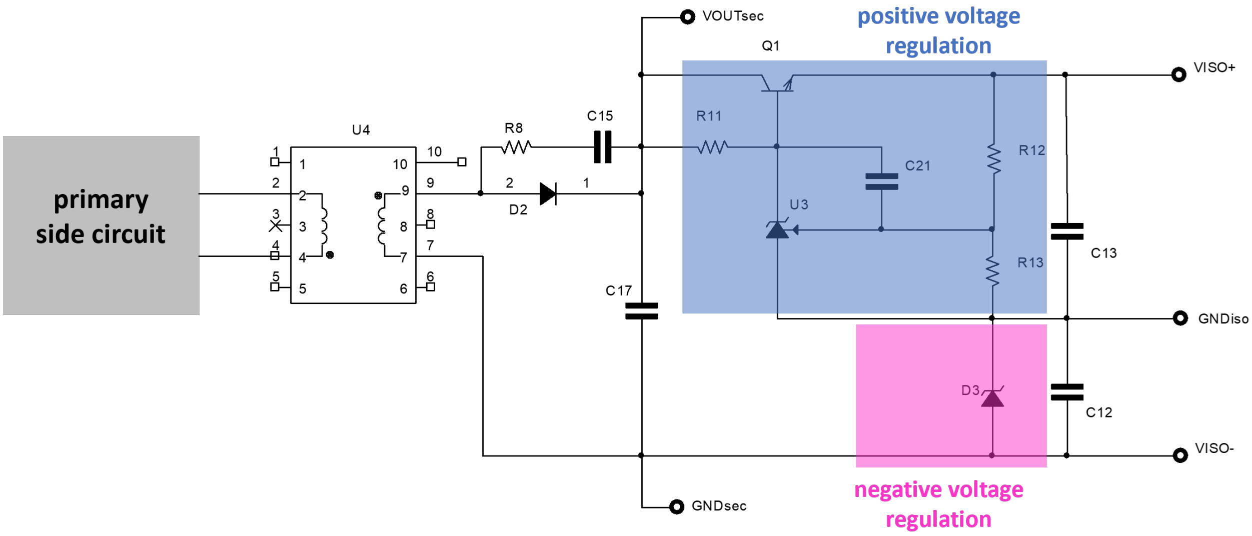
- Primary output voltage must be lower than the input voltage (by definition since it is a buck converter)
- Primary output voltage must be low enough to match the duty cycle constraints described in Section 1
- Lowering the primary output voltage requires a higher turn ratio, making the transformer bigger or affecting other electrical parameters (for example, series resistance)
- A higher turn ratio means a higher current peak and less margin from the current limit thresholds, hence a lower isolated output current capability.

The isobuck-boost overcomes all the above-mentioned constraints.

Example 1. V_{IN} = 8 V to 14 V, isolated voltage +20 / -5 V (then indicated respectively as V_{ISO+} and V_{ISO-}), isolated output current 100 mA. For this example, the STEVAL-A6986IV1 or STEVAL-L6986IV1 have been used as reference.

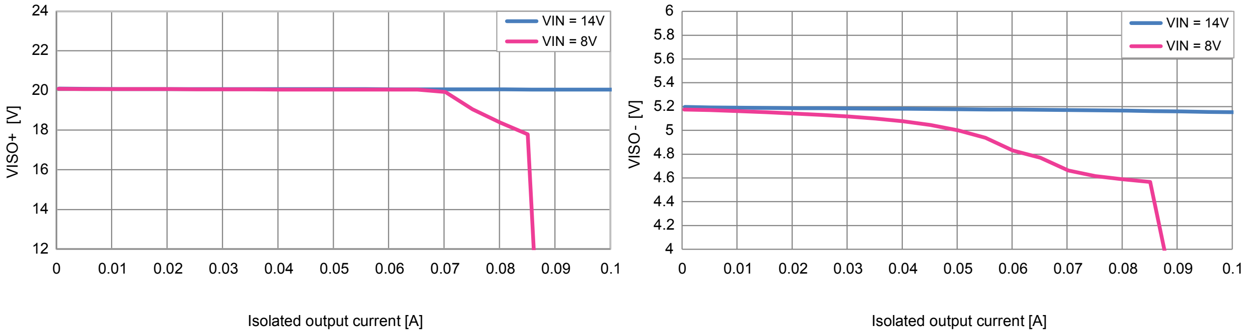
1. In order to match the recommended maximum duty cycle (below 70%), the primary output voltage should be regulated below 5.6 V ==> V_{OUT_prim} = 5.3 V.
2. The secondary winding can be single (the solution here proposed) or there can be two windings. In both cases, for a good load regulation and voltage accuracy, a post-regulation circuitry is necessary.
3. The voltage at the secondary winding should be sufficiently higher than the sum 20 V +5 V = 25 V to consider the losses of the post-regulation, the voltage drop of the Schottky diode, and other losses and parasitic effects. Therefore, a transformer with a turn ratio around 5.8 is selected.

Figure 15. **Example of a post-regulation circuit used to generate the dual voltage +20 V / -5 V**



The use of an isobuck solution would fit the upper value of the input voltage range (14 V) in this case, but not the lower one (8 V). Load regulation performance is shown in Figure 16:

Figure 16. **Load regulation for the positive (left, V_{ISO+}) and the negative (right, V_{ISO-}) isolated voltages at the extreme values of the V_{IN} range, isobuck solution**



With V_{IN} = 8 V, the minimum value of the reverse current limit is already exceeded with a load of around 50 mA. Moreover, the high duty cycle limits the energy transfer to the secondary side, causing both the V_{ISO+} and V_{ISO-} to drop.

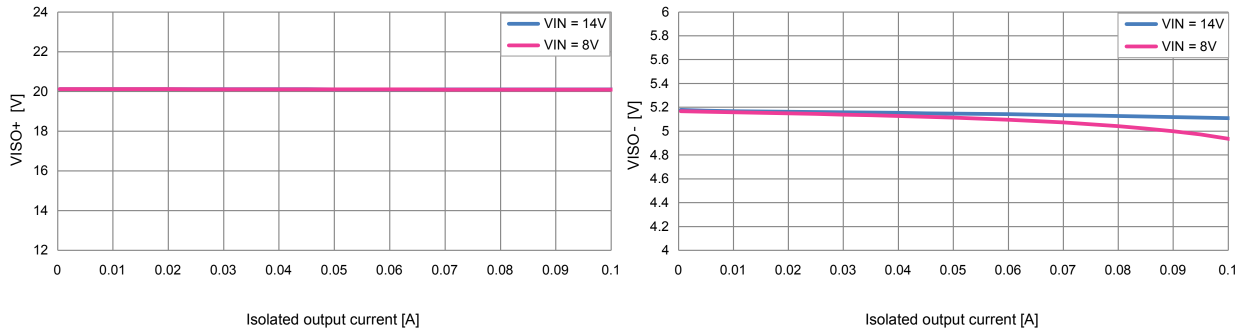
Using instead the isobuck-boost, and regulating, for instance, -13 V at the primary output, the duty cycle is then:

$$D = \frac{|V_{OUT}|}{|V_{OUT}| + V_{IN}} = \begin{cases} 62\%\ for\ V_{IN} = 8V \\ 48\%\ for\ V_{IN} = 14V \end{cases} \quad (4)$$

The possibility to overcome the constraint of regulating a voltage lower than V_{IN}, due to the inverting buck-boost architecture, also allows an optimization of the transformer design. In this case a much lower turn ratio can be used (for example, in the measurement shown below N = 2.38), hence leading to a smaller size and limiting the current peaks in the windings.

Load regulation graphs (below) show the stability of both V_{ISO+} and V_{ISO-}. Moreover, under these conditions a wider margin from the reverse current limit is achieved.

Figure 17. **Load regulation for the positive (left, V_{ISO+}) and the negative (right, V_{ISO-}) isolated voltages at the extreme values of the V_{IN} range, isobuck-boost solution**

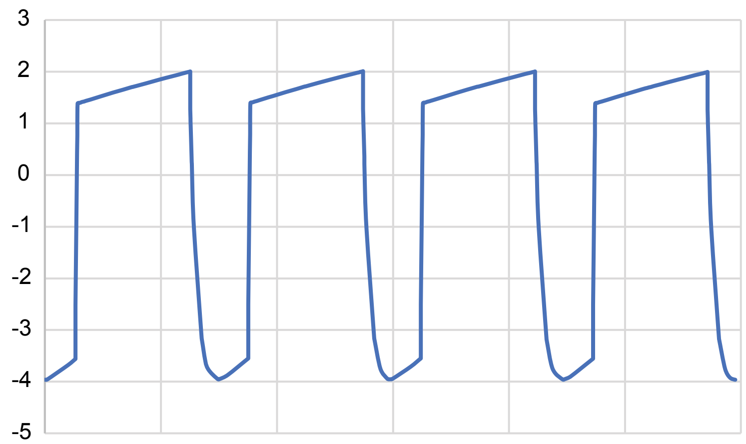


Example 2. V_{IN} = 5 V, isolated voltage 5 V with a not defined load. For this example the A/L6983I is considered (see reference schematic in Figure 13).

Using the isobuck solution and regulating 3.3 V at the primary not isolated output, the maximum deliverable current (limited by the reverse current limit) would be around 500 mA, setting the switching frequency to 200 kHz (lower frequency allows higher deliverable power). The transformer in this case should have a turn ratio of 3.4.

Here below the primary winding waveform under this condition (rms current 2.2 A).

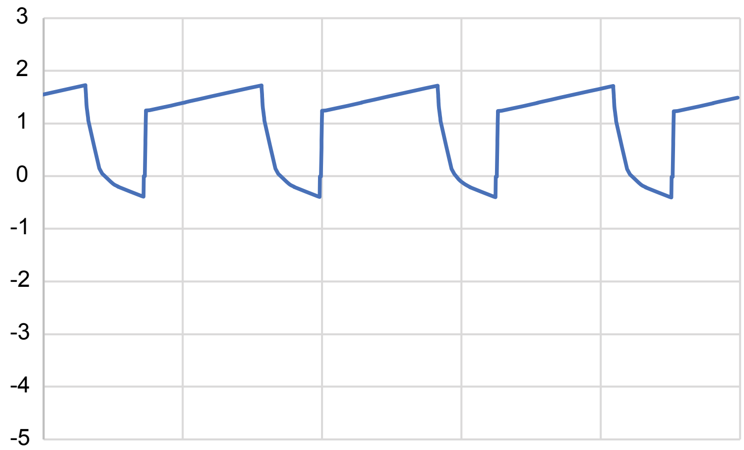
Figure 18. **Primary winding current waveform with A/L6983I with isobuck architecture**



Implementing an isobuck-boost architecture, it is possible to reach the same deliverable current by setting the primary output voltage to -9 V and the frequency to 400 kHz. In this case, a 1:1 transformer could be used.

The primary winding current waveform is shown in Figure 19 (rms current 1.2 A).

Figure 19. **Primary winding current waveform with A/L6983I with isobuck-boost architecture**



The advantages of using the isobuck-boost instead of using the isobuck in this case are multiple:

- Lower rms current in the primary winding
- Possibility to use a 1:1 transformer (more likely to be found within off-the-shelf transformers)
- Lower turn ratio and higher switching frequency (400 kHz vs. 200 kHz) help to reduce the transformer size
- Using the default switching frequency saves one component (resistor)
- Possibility to deliver higher power, if required (significant room from the current protection thresholds).

The maximum deliverable current using the isobuck-boost architecture is around 850 mA by setting the primary output voltage to -13.5 V, switching frequency to 400 kHz, turn ratio 1:1.

Below, the primary winding current waveform under these conditions (rms current 3 A).

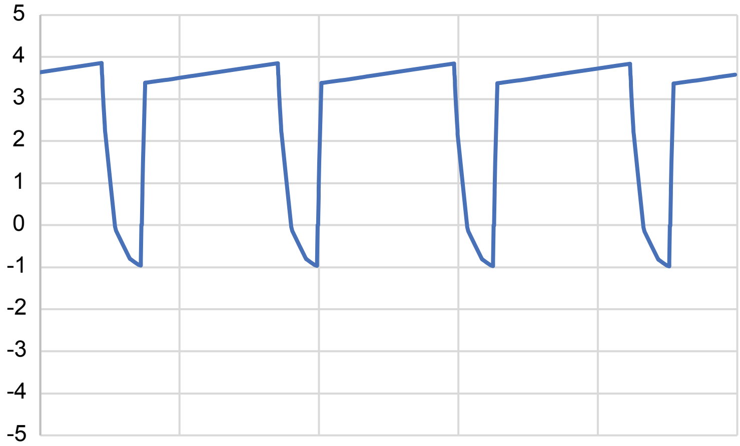


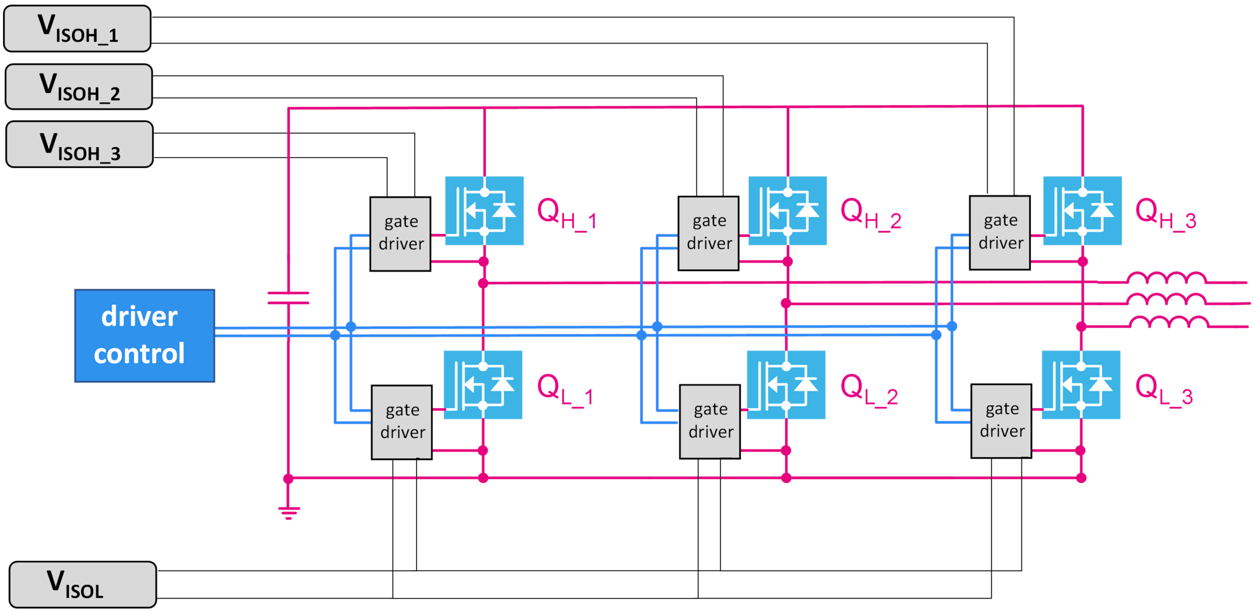
Figure 20. **Primary current winding with A/L6983I used as isobuck-boost at the maximum deliverable current**

5.2 Supplying three-phase drivers

Supplying three-phase systems (for example, for three-phase inverters) implies the generation of the dedicated isolated voltages for the three high-side drivers and the three low-side drivers.

In the application idea shown below, the three low-side drivers can share the ground together, so that a single supply voltage (dual) is enough for them.

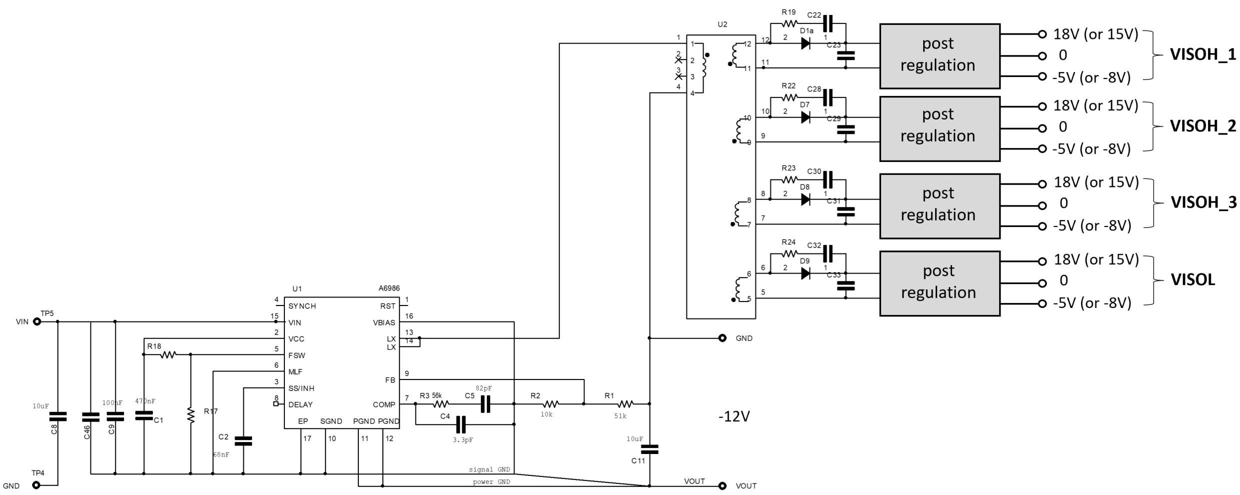
Figure 21. Example of the supply of a three-phase half-bridge system



The power demand of such a system makes the isobuck-boost the most suitable architecture.

The schematic below depicts a possible solution with A/L6986I.

Figure 22. Schematic of the isobuck-boost with A/L6986I for three-phase drivers' supply



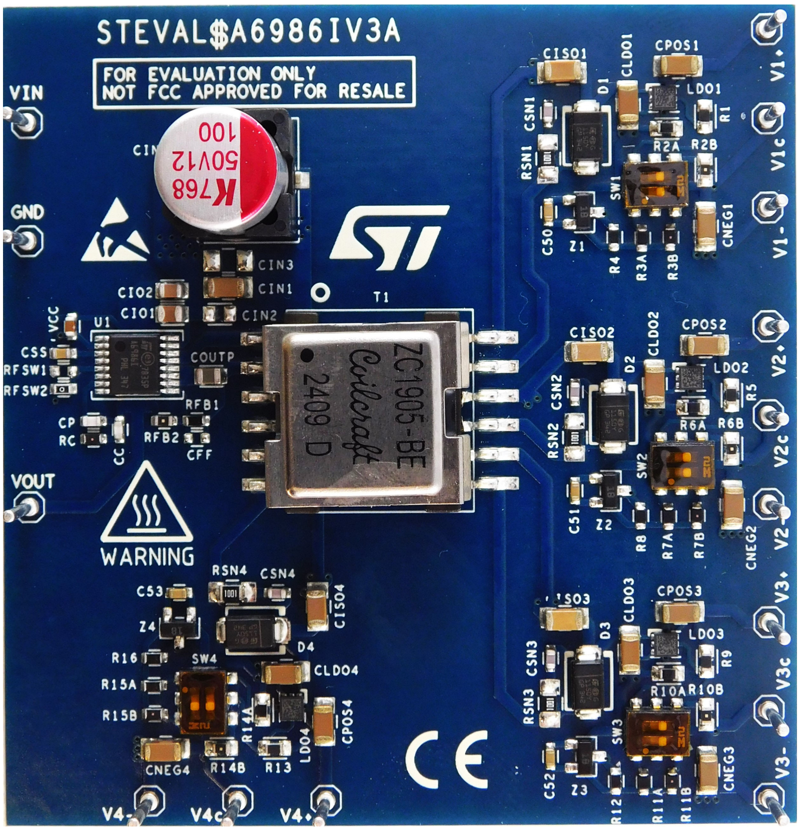
The choice of the primary output voltage (in this case around -12 V) is the outcome of the optimization of the solution considering transformer parameters, size, and best exploitation of the current capability of the A/L6986I.

Each secondary winding has the same number of turns (N = 2.6), so that the turn ratio between the primary winding and each secondary one is identical. Downstream of the secondary side filter, a post-regulation circuit is used in order to generate the dual voltage +20 V and -5 V.

The solution object of this example is also available as an orderable demoboard (STEVAL-A6986IV3).

An image of the STEVAL-A6986IV3 is shown in Figure 23. STEVAL-A6986IV3

Figure 23. **STEVAL-A6986IV3**



Here below, the main features of the STEVAL-A6986IV3 are summarized:

- 4 V to 28 V operating input voltage
- Four isolated outputs with regulated dual voltage
- Selectable isolated voltage pairs: 18 V/-5 V or 15 V/-8 V deliverable current up to 60 mA for the first three channels and 180 mA for the fourth one.

The detailed features and the performance of the STEVAL-A6986IV3 are depicted in the dedicated user manual (UM3440).

6 Conclusions

The use of the isobuck-boost architecture should be considered in all applications where:

- Low input voltage or extreme duty cycle conditions represent a strong limitation in regulating the required voltages and/or deliver the requested current
- A better exploitation of the current capability is necessary to fulfill isolated output load demands
- The primary output not isolated voltage is not used as auxiliary voltage in the system
- An optimization of the transformer is desired, by reducing the turn ratio and possibly its size.

Revision history

Table 2. **Document revision history**

Date	Version	Changes
10-Oct-2024	1	Initial release.

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