Commentary

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Transitioning Voltage Regulator Design From Unidirectional To Bidirectional

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Energy management systems (EMSs) are an emerging set of applications aimed at optimizing the energy flow and storage between electric vehicles, photovoltaic systems, home storage batteries and the electric grid. Such flexible energy management requires that fundamental blocks like voltage regulators and chargers, connected to the EMSs, operate bidirectionally with respect to the energy flow.

However, the vast majority of today's blocks power traditional unidirectional loads like CPUs, motherboards, stationary and mobile devices. In these applications, the current and the associated energy flows unidirectionally from an input voltage source, which can have a wide range of operation, to a tightly regulated output powering a passive load.

Understandably, the IC or system designer approaching this emerging field coming from such traditional applications may need some mindset adjustment with respect to bidirectionality. A designer that has thus far designed only unidirectional PWM buck converters will find himself/herself in a quite unchartered territory when asked to design an eminently bidirectional phase-shift dual active bridge (DAB) converter.

Hence, designers looking to do their first bidirectional converter designs may benefit from some background on how these relate to conventional, unidirectional power converters. As we'll see, there are already elements of bidirectional energy flow in the familiar unidirectional converters.

Hints Of Bidirectional Energy Flow In Traditional Control

In truth bidirectional energy flow is never completely absent from traditional applications. Take for example the case of a synchronously rectified, stepdown switching regulator powering a CPU. Even here, we actually encounter energy flow inversion at light load, when the inductor current ripple peak exceeds the load dc current. This may create output voltage dips that compromise the voltage regulation and also affect efficiency. Such "annoyance" requires a little extra design effort in order to disable synchronous operation at light load.

Another example is a PWM full-bridge motor driver, where the motor current is routinely built-up during the on time and recirculated back to the input during the off-time. Such energy "pump back" at off-time is again a concern as the full-bridge driver input capacitor may overcharge and exceed the driver IC breakdown voltage.

The above examples hint that synchronous power trains are inherently bidirectional in nature and the annoying energy flow inversion effect can actually become a feature in EMS applications.

In the following section, we move the discussion progressively from a typical unidirectional buck converter topology to a predominantly bidirectional one like the phase-shift DAB. While the difference between the two topologies is substantial, we will focus on the similarities and highlight how elements of bidirectionality are already present in the former and are then fully brought to bear in the latter.

Half-Bridge Power Train Bidirectionality

Fig. 1 is the simplified block diagram of a 12-V-to-1.8-V synchronously rectified buck converter (left). The associated current and switching node waveforms for a typical load are on the right. The placement of the feedback network and the load (not shown) at the 1.8-V node defines this configuration as a buck converter. Here the current comes out of the input node V2 and flows into the output node V1.

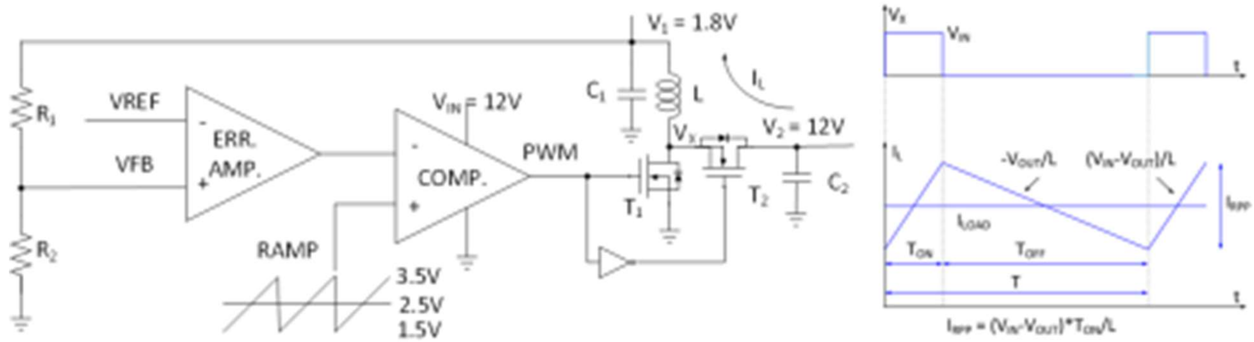


Fig. 1. Synchronous buck converter and waveforms for a typical load.

Fig. 2 shows the circuit's waveforms in the presence of a load so light that the current ripple is partly negative (red highlight). During this dip, the current is negative, effectively flowing from the output node V1 into the input node V2.

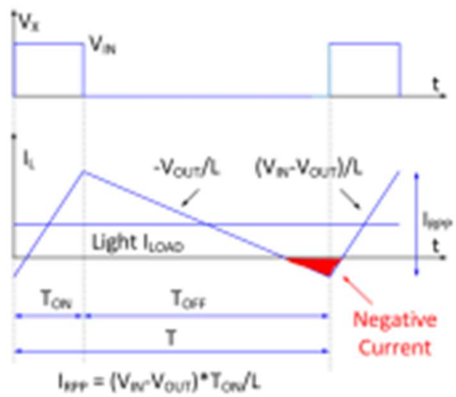


Fig. 2. Light load waveforms for the synchronous buck converter.

Fig. 3 shows the same circuit of Fig. 1 but with input and output reversed. Here the placement of the feedback network, and the load (not shown), on the 12-V node defines this configuration as a boost converter. Notice how the inductor current flow here is reversed compared to the buck converter of Fig. 1. Now the current comes out of V1 and into V2.

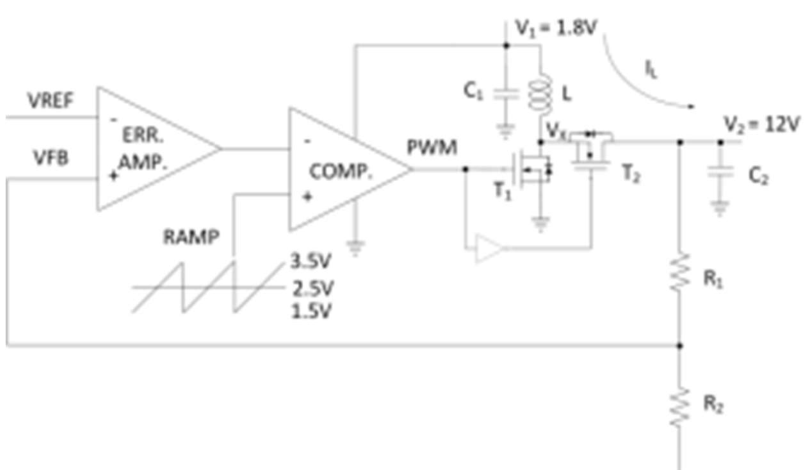


Fig. 3. Synchronous boost converter with input and output reversed.

The inherent bidirectionality of the synchronous rectifier power train (T1, T2) yields seamlessly two quite opposite configurations like the buck and the boost converter. It follows that the same power train should be able to handle both configurations concurrently, namely, given a high-voltage and a low-voltage node, this circuit can exchange energy between the two nodes as shown in Fig. 4.

As an example, the circuit in Fig. 4 represents an application in which two storage devices, a 1.8-V battery and a 12-V battery, are monitored so that if one battery is depleted, the other one recharges it.

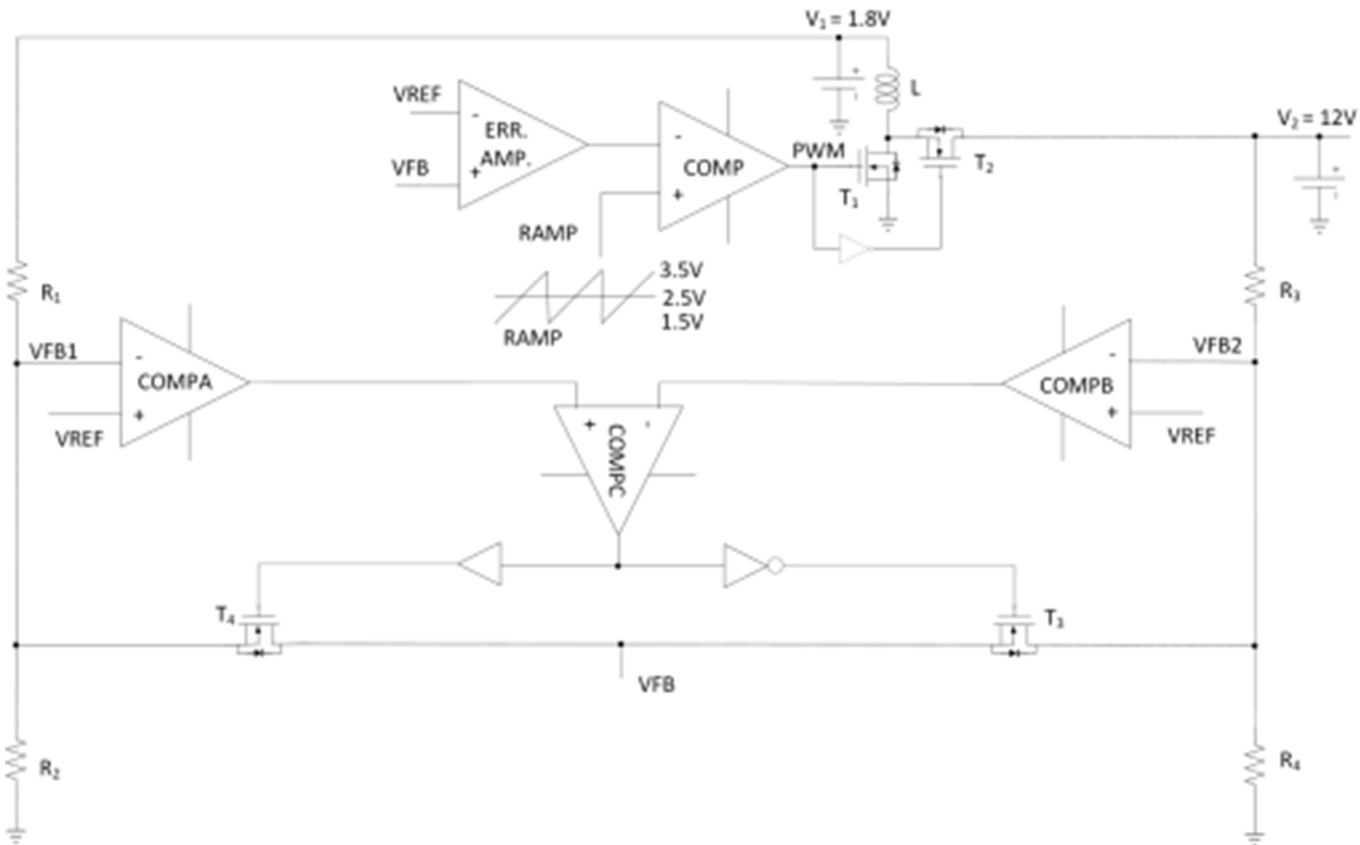


Fig. 4. Bidirectional energy flow between two storage devices.

From Hard Switched To Soft Switched

The circuits discussed above typically have hard-switched, lossy transitions of the V_x switching node, hence they have efficiency limitations especially in high-power applications. Actually, referring again to Fig. 2, during current reversal the low-to-high transition of the Vx node is helped by that negative current, as that node is losslessly bootstrapped from ground to the power rail by that current: effectively a zero-voltage-switching (ZVS) transition, assuming the current is high enough to charge the switching node up to the positive rail.

But as mentioned earlier, the current reversal robs current from the load, and the soft switch only happens in the presence of exceedingly high current ripple compared to the dc current, hence it is of no practical value in this topology. The solution is to fully embrace the current inversion in a two-stage switching solution in which the first stage generates a 50% duty cycle, zero-average square-wave current, which enables soft switching transitions. This current is then rectified in the second stage, delivering a dc current to the load.

Dual Active Bridge

A practical implementation of this strategy is the phase-shift DAB. Fig. 5 shows the isolated DAB system block diagram in high detail.

Two phase-shift modulation (PSM) control chains (two-channel), one on the V1 port and the other on the V2 port, allow for control of that port when designated as an output. If the V1 port is controlled, then the associated PSM chain is active, and vice versa. Each PSM chain, when active, controls the bidirectional flow of energy from primary to secondary, and vice versa. The port control is selected via a select pin (not shown).

The two bridges (bridge S1A, S2A, S1B, S2B and bridge S3A, S4A, S3B, S4B) are isolated by the high-voltage transformer T. Differential amplifiers (DAs) sense the inputs of the controlled port, compare them to a reference voltage V_{REF} and feed them back to the proportional-integral (PI) compensation blocks. Appropriate dead-timegeneration (DTG) eliminates the possibility of shoot-through (i.e., shorts) between high-side FETs and low-side FETs in the half-bridge totem poles.

Auxiliary flyback (FB) converters, followed by linear regulators (LR), assure accurate, IC-process-independent high-voltage, high-side FET bootstrap, while pulse transformer isolation (PT5, PT6) enables the low-voltage feedback paths between primary and secondary side. Four pulse transformers (PT1 through PT4) transmit the signal commands from low- to high-side sections.

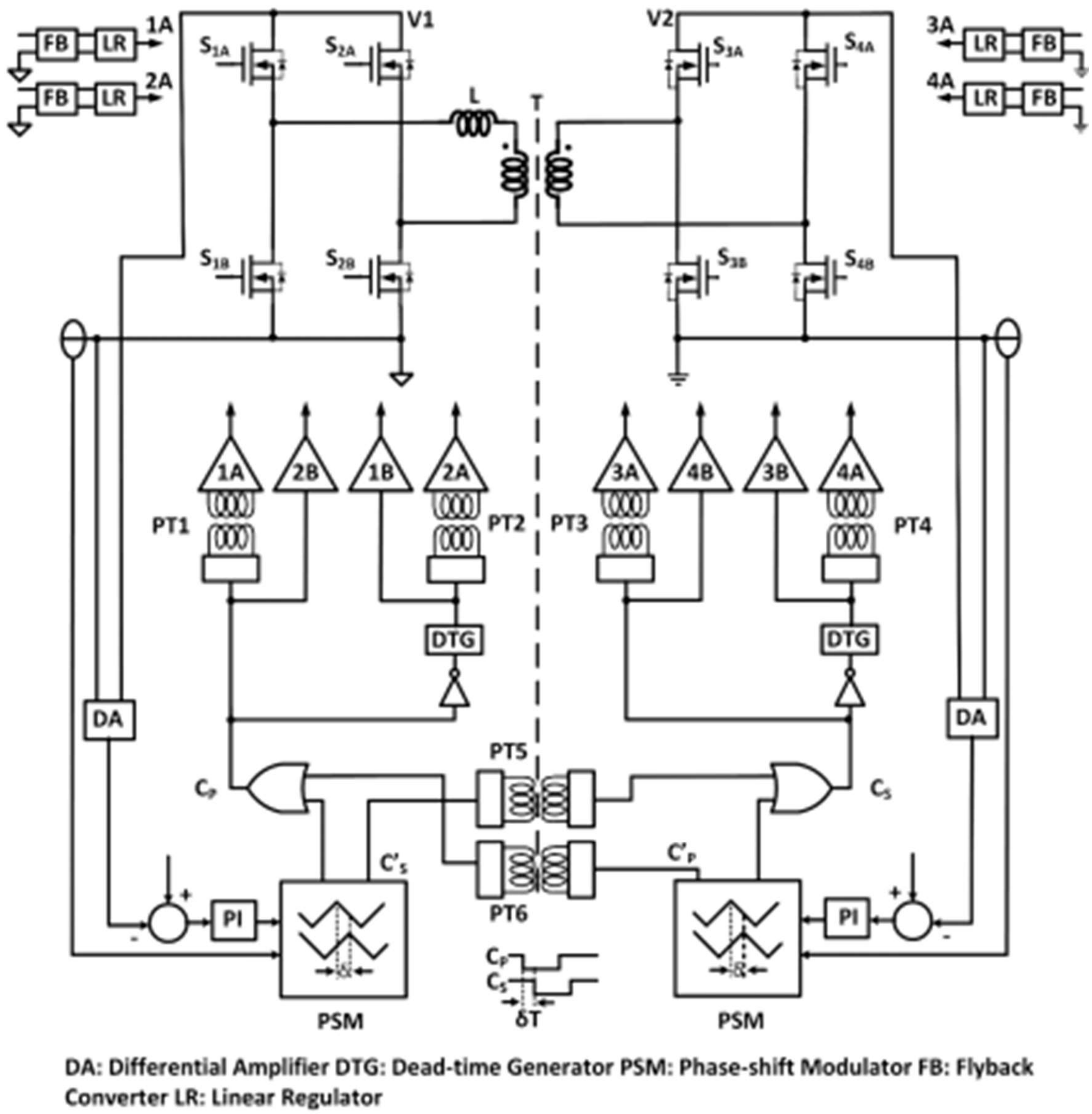
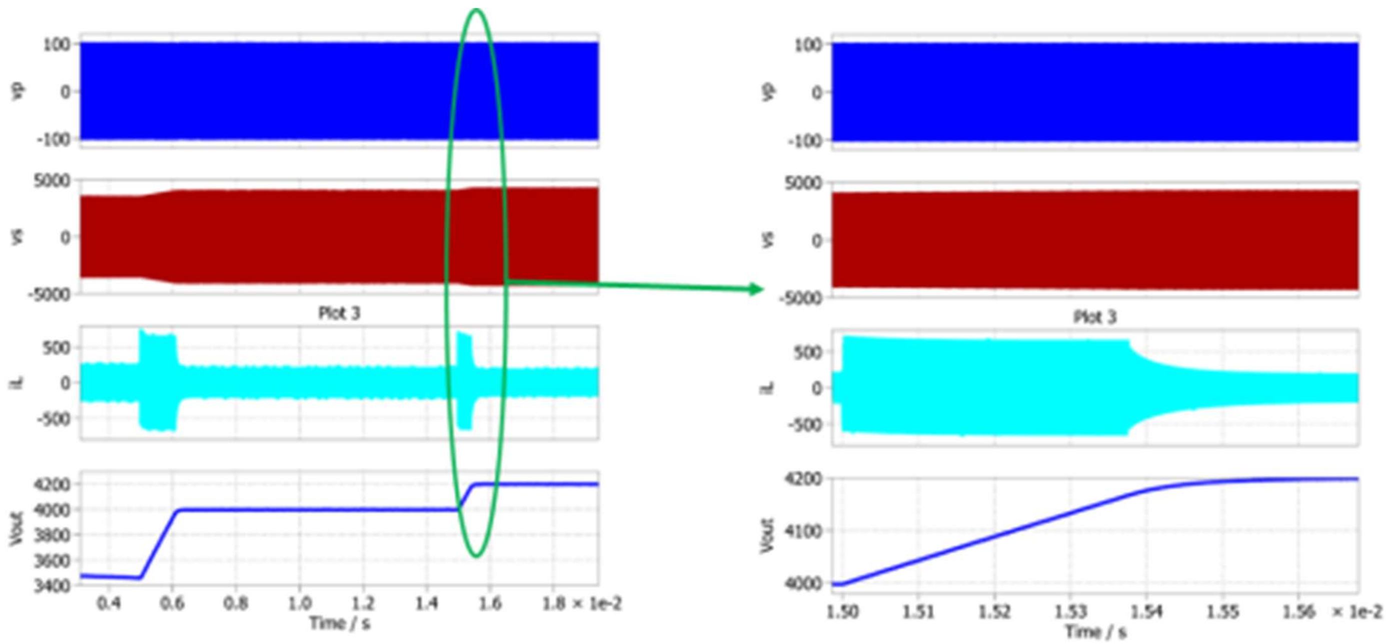


Fig. 5. Dual active bridge system.

A PLECS modeling system simulation yields the waveforms in Fig. 6. This simulation refers to a commercial application for grid-tied and off-grid energy storage systems, addressing high-voltage operation enabling high dc conversion gain from 100 V to a 5000-V dc link voltage.

Focusing on the waveforms on the left, vp and vs (the top two waveforms, in blue and red, respectively) are the primary and secondary voltages directly across the transformer primary and secondary windings. The third waveform from the top in green, IL, is the load current, while the bottom waveform in blue, Vout, is the output voltage.

Vout is increased by successive steps and correspondingly, during each step, the IL current peaks to charge the output capacitors to the next voltage level. Now, turning our attention to the waveforms on the right side, these are blow-ups of a section of the waveforms on the left side.



$$V_{in} = 100 \text{ V}, \ n = \frac{1}{50}, \ L = 150 \text{ nH}, \ R = 2500\ \Omega, \ C = 10 \text{ uF}, \ \text{GCF}= 2 \text{ kHz}, \ \text{PM}=85 \text{ degree}$$

Fig. 6. DAB closed-loop simulations.

As shown in Fig. 6, the current is bipolar, enabling soft switching as discussed above.

Incidentally, the DAB control algorithm could go either way, namely PWM or phase shift. The phase-shift implementation is preferred because it enables operation at fixed frequency and 50% duty-cycle. Accordingly, this control generates easier to filter odd harmonics, the gate drivers are easier to design, and the soft transitions involve only one diode (versus two in PWM), leading to better efficiency.

Since the switching node bootstrap is performed by the current, ZVS can only be sustained with mid to high levels of load currents. Accordingly, this topology can achieve spectacular efficiencies at full load, with some degradation at light load.

Conclusion

Applications and markets requiring bidirectional energy flow are emerging. A chip or system designer that previously worked only with classic, unidirectional applications, today may suddenly face a novel request: the customer is asking for a bidirectional energy controller IC, and yes, in six months or less. Naturally, the designer will scour the internet, talk to some senior colleagues, read everything possible about DABs and deliver to the best of his/her abilities.

Because of the constraints of the designers' busy schedules, they may not have the time to stop and think: what happened? How did we go from point A to point B? How did we go from one-way to two-way energy flow control?

It turns out that many of the tools in the designer's toolbox, like the ubiquitous half-bridge synchronous rectification power train, are inherently bidirectional to start with, although in a simplified way. And a full bridge is just the sum of two half bridges. It takes just a few leaps of imagination to go from a basic manifestation of a bidirectional control into a full-fledged, mature and usable one, based on the phase-shifted DAB control architecture or other similar architectures.

Acknowledgement

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About The Author

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For more on designing bidirectional power converters, see How2Power's Design Guide, and enter "bidirectional" in the keyword search. Also see parts 2 and 4 of the series "Developing A 25-kW SiC-Based Fast DC Charger" which discusses design of the dual active bridge.

