

Achieve Bidirectional Control and Protection Through Back-to-Back Connected eFuse Devices

Rakesh Panguloori

ABSTRACT

Applications such as high-side battery switching demands a power switch capable of bidirectional current flow, bidirectional voltage blocking for proper power management. This application report starts with the definition and V-I characteristics of an ideal bidirectional power switch (BPS), followed by common circuit configurations to achieve BPS characteristics.

This report highlights the challenges and limitations of existing implementations and discusses how eFuse devices can be used to improve power path protection and control. At the end, test waveforms demonstrating the performance and bidirectional power switch functionality of eFuse solution are presented.

Contents

1	What is a Bidirectional Power Switch?	2
2	Bidirectional Power Switch Applications	3
3	BPS Discrete Implementations.....	4
4	BPS Realization With eFuse Devices	5
5	Test Results	7
6	Conclusion	9
7	References	9

List of Figures

1	Bidirectional Power Switch – Ideal Representation	2
2	Bidirectional Power Switch – Characteristics in ON State	2
3	Bidirectional Power Switch – Characteristics in OFF State	2
4	BPS Configuration – P-MOSFET Through Body Bias	2
5	BPS Configuration – Back-to-Back Connected P-MOSFETs	2
6	BPS Configuration – N-MOSFET Through Body Bias	3
7	BPS Configuration – Back-to-Back Connected N-MOSFETs in Common-Source Configuration.....	3
8	BPS Configuration – Back-to-Back Connected N-MOSFETs in Common-Drain Configuration.....	3
9	Charger Demultiplexing BPS.....	3
10	High-Side Battery Switching BPS	3
11	BPS in Standby Power System	4
12	BPS Discrete Implementation Using Back-to-Back Connected P-MOSFETs	4
13	Discrete Implementation of BPS Using N-MOSFETs	5
14	BPS Realization Using Back-to-Back Connected eFuse Devices.....	5
15	Output Characteristics at the Terminals ‘A’ and ‘B’ of the eFuse Solution.....	6
16	System Start-up From Battery	7
17	Inrush Current Profile With Load	7
18	Overload Protection for Battery	7
19	Overload Response of eFuse Solution When Load Resistance is Changed from 100 Ω to 5 Ω	7
20	Short-Circuit Protection for Battery.....	7

21	Output Hot Short to GND Response	7
22	Battery Current During Charger Plug-in Event.....	8
23	Current Profile of the Battery Path During Charger Plug-In	8
24	Charger Demultiplexing for Two Batteries.....	8
25	Current Profile of Battery #1, BPS #2 is in Disable Mode	8

List of Tables

Trademarks

All trademarks are the property of their respective owners.

1 What is a Bidirectional Power Switch?

A bidirectional power switch (BPS) is an active switch which can support bidirectional current flow when it is in the ON condition and bidirectional voltage blocking when it is turned OFF. Figure 1 shows an ideal representation of BPS with 'A' or 'B' as interchangeable input/output terminals. The characteristics of BPS in the ON state, OFF state are illustrated in Figure 2 and Figure 3, respectively. In *Power Electronics* terminology, bidirectional power switch is termed as a four-quadrant switch capable of conducting positive or negative ON-state current and capable of blocking positive or negative OFF-state voltage.

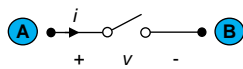


Figure 1. Bidirectional Power Switch – Ideal Representation

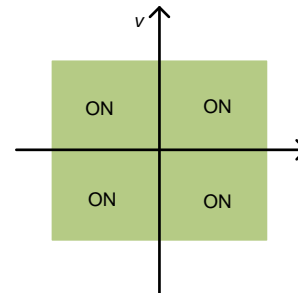


Figure 2. Bidirectional Power Switch – Characteristics in ON State

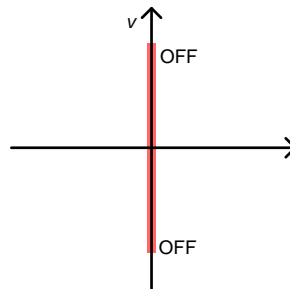


Figure 3. Bidirectional Power Switch – Characteristics in OFF State

Figure 4 through Figure 8 show common circuit configurations which can be used to realize BPS. As shown in Figure 4, a simple P-channel MOSFET with a body bias selector circuit facilitates BPS function. The circuit automatically biases the P-channel body to the most positive potential (source or the drain) to maintain a reverse bias across the diode present between the source and the drain terminals. Similarly, an N-channel MOSFET with its body connected to the most negative potential (Figure 6) in the circuit can support BPS function. The back-to-back connected MOSFETs either in common source or common-drain configuration as shown in Figure 5, Figure 7, and Figure 8, provides symmetrical OFF-state blocking characteristics similar to bidirectional power switch.

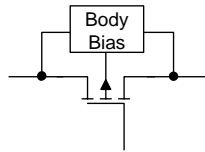


Figure 4. BPS Configuration – P-MOSFET Through Body Bias

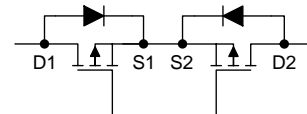


Figure 5. BPS Configuration – Back-to-Back Connected P-MOSFETs

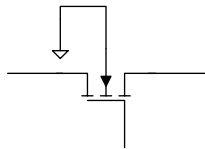


Figure 6. BPS Configuration – N-MOSFET Through Body Bias

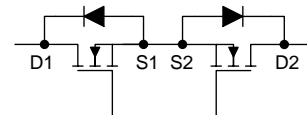


Figure 7. BPS Configuration – Back-to-Back Connected N-MOSFETs in Common-Source Configuration

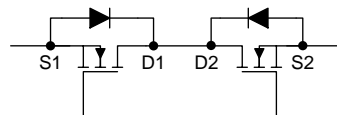


Figure 8. BPS Configuration – Back-to-Back Connected N-MOSFETs in Common-Drain Configuration

2 Bidirectional Power Switch Applications

In this section, some application use cases of bidirectional power switches are presented. Figure 9 shows an application of a bidirectional power switch for charger demultiplexing. A single charger is utilized for charging multiple battery units in a sequential manner. In this use case, the BPS should be able to block voltage in OFF-state to avoid draining a charged battery or to avoid one battery from charging another battery. Figure 10 illustrates the usage of BPS for high-side battery switching in portable products, where one of the battery sources is selected to power the load.

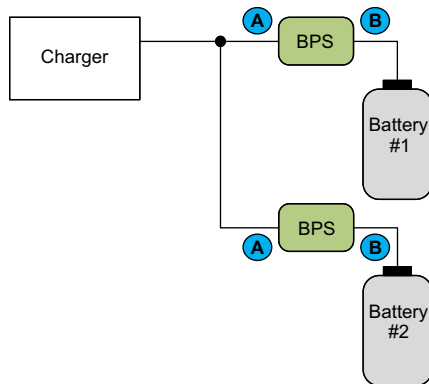


Figure 9. Charger Demultiplexing BPS

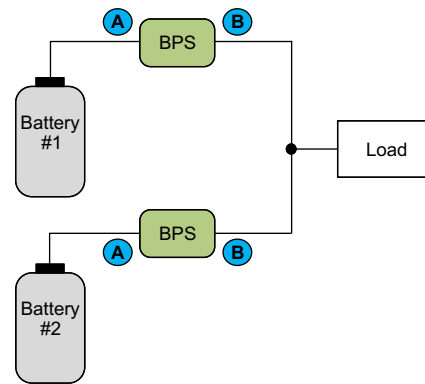


Figure 10. High-Side Battery Switching BPS

Figure 11 shows another use case of BPS in a standby power system. The supervisory circuit monitors the system status and disconnects the battery from the main circuit in sleep mode. This helps save precious battery energy by avoiding leaking current from the battery. In this use case, the BPS should draw very low shut-down current. When the battery is connected back to the main circuit, the BPS should be able to provide inrush current protection.

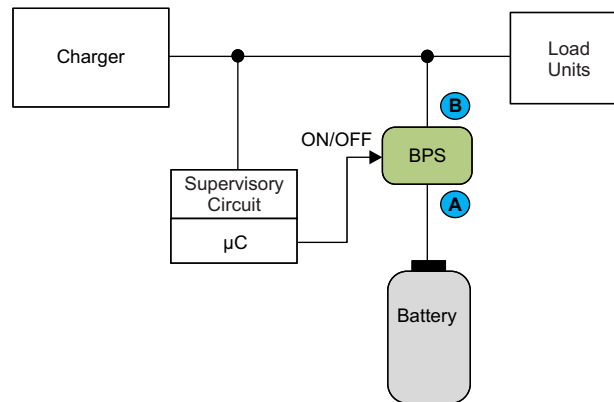


Figure 11. BPS in Standby Power System

As seen in these application use cases, the other performance-related requirements of bidirectional power switch are:

- The BPS device should have flexibility to enable the power flow from either 'A' or 'B', which means the device should be able to turn on the path when powered at terminal 'B', even if potential at 'A' = 0 V.
- In battery-powered systems, the BPS should provide low on-state resistance R_{on} for tight voltage regulation during charging phase and for better battery capacity utilization in back-up mode.
- The BPS device is always connected to the battery side, so it should draw very low shut-down current.
- When the battery is connected back to the system, momentary inrush current is expected on the battery which can stress the BPS device. Any additional protection against inrush currents, overloads, short circuit, and temperature enhances the reliability of the system.

3 BPS Discrete Implementations

Figure 12 shows a discrete implementation of a bidirectional power switch using P-channel MOSFETs. In this solution, the body diodes of P-MOSFETs assist in enabling the power flow from either 'A' or 'B'. This implementation is simple and an additional capacitor at the gate terminal helps in controlling the inrush current in both the power flow directions. However the P-MOSFET solution is more expensive than N-MOSFET to achieve same ON-state resistance. The circuit does not have thermal protection for the FETs, so, an oversized device needs to be considered for higher design margin.

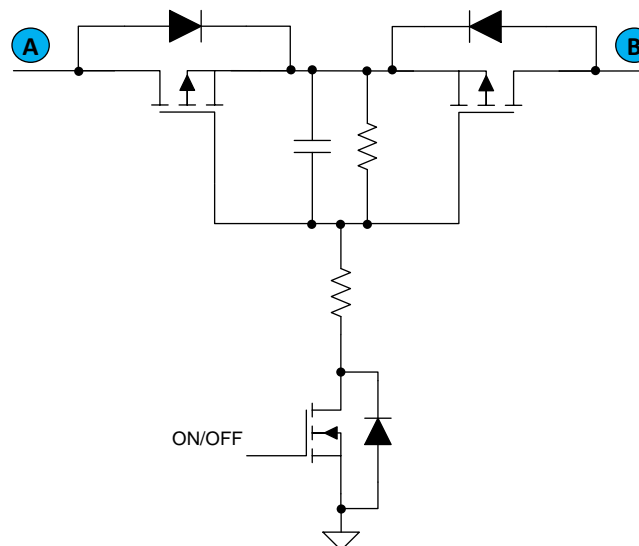


Figure 12. BPS Discrete Implementation Using Back-to-Back Connected P-MOSFETs

The discrete implementation of bidirectional power switch using back-to-back connected N-channel MOSFETs is illustrated in Figure 13. In this solution, an additional circuitry is used to support the power flow either from terminal 'A' or 'B'. The Schottky diodes MUX the supplies at terminals 'A' and 'B' to power the charge pump circuit, which in turn provides enough gate drive to turn ON both the N-channel MOSFETs. Even though the implementation provides low R_{on} with N-MOSFETs but the component-intensive complex drive circuit occupies more board space and also raises concern on circuit robustness. Similar to Figure 13, this circuit also does not provide thermal protection for the FET, so oversized FETs need to be considered for higher design margin.

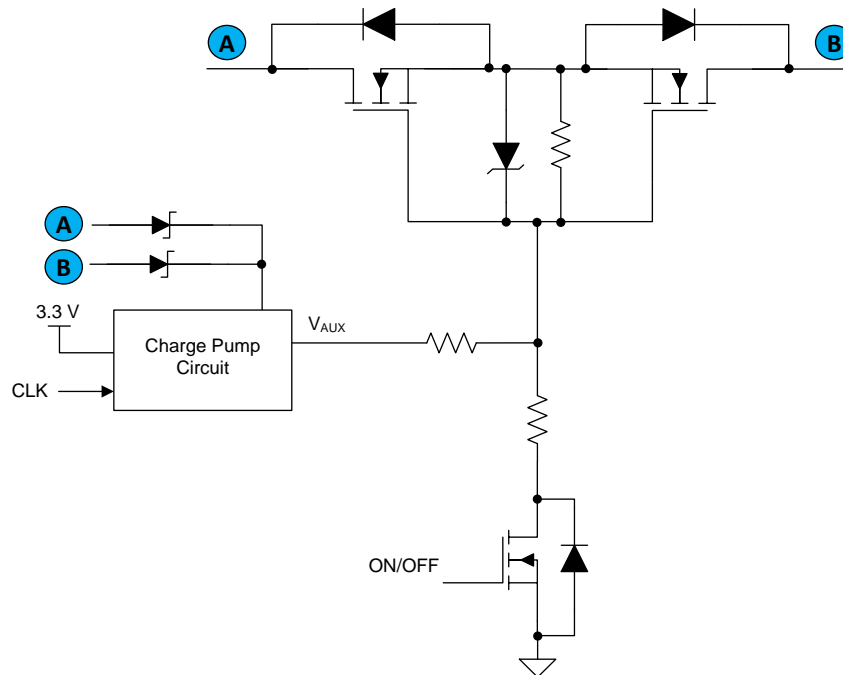
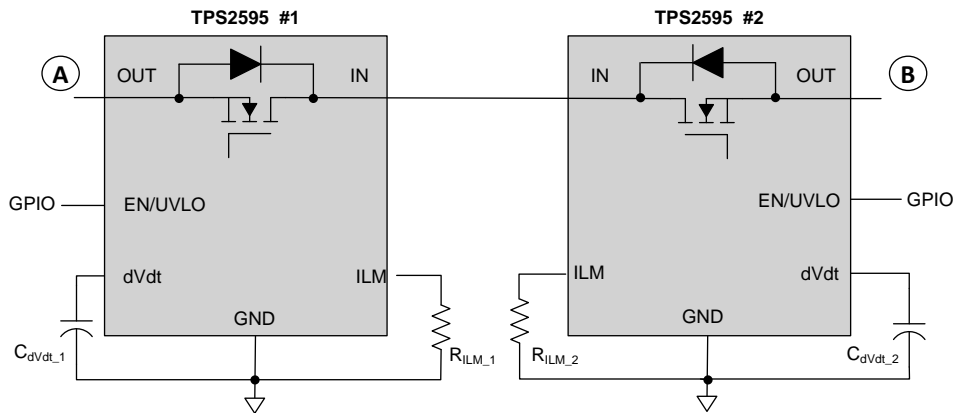


Figure 13. Discrete Implementation of BPS Using N-MOSFETs

4 BPS Realization With eFuse Devices

Figure 14 shows realization of bidirectional power switch using TPS2595 eFuse devices. Two eFuse devices are connected in back-to-back configuration to support OFF-state voltage blocking. When the applied voltage at the 'A' or 'B' terminal exceeds a minimum operating voltage of 2.7 V, the circuit configuration establishes the power path connection.



Copyright © 2017, Texas Instruments Incorporated

Figure 14. BPS Realization Using Back-to-Back Connected eFuse Devices

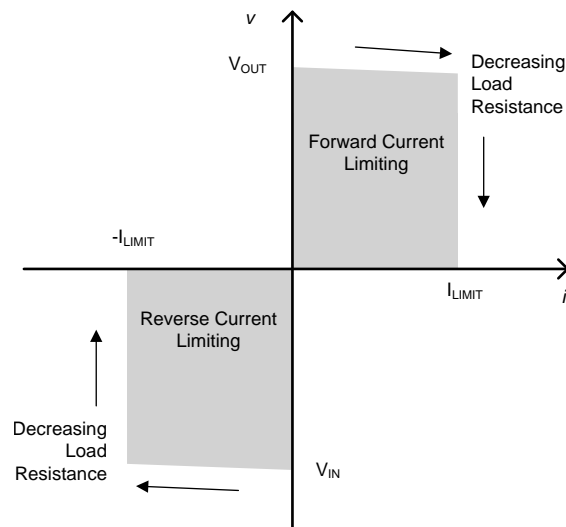


Figure 15. Output Characteristics at the Terminals 'A' and 'B' of the eFuse Solution

The terminal characteristics of eFuse solution are symmetric at both the ports as shown in Figure 15. Apart from supporting bidirectional current flow and OFF-state voltage blocking, the eFuse solution offers additional protection which includes overcurrent limiting, short-circuit protection, and inrush current control, and so forth. As seen in Figure 15, the terminal voltage decreases with the increase in the load current due to ON-state voltage drop. Any further increase in load current beyond the programmed current trip point I_{LIMIT} pushes the device into current-limiting mode. During current-limit mode of operation, the device effectively regulates the output current to I_{LIMIT} causing the terminal voltage to drop accordingly.

eFuse solution advantages follow:

- N-MOSFET offers superior ON-state resistance
- The wide operating voltage from 2.7 V to 18 V makes the TPS2595 device compatible to Li-Ion, lead-acid battery applications
- The integrated thermal protection ensures device operation to be within the *Safe Operating Area* (SOA) limits
- Two back-to-back connected eFuse devices gives freedom to set independent forward and reverse overload current limits
- The eFuse solution provides quick termination of transient short-circuit currents and offers robust short-circuit protection

4.1 Setting Current Limit

The TPS2595 device monitors load current during start-up and the normal operation. When the load current exceeds the current limit trip point I_{LIMIT} programmed by the R_{ILM} resistor, the device regulates the current to the set limit I_{LIMIT} . Use Equation 1 to find the R_{ILM} value for a desired current limit.

$$R_{ILM} = \frac{2000}{I_{LIMIT} - 0.04} \quad (1)$$

4.2 Setting Slew Rate and Inrush Current Control

The inrush current during turn on is directly proportional to the load capacitance C_{OUT} and rising slew rate. Use Equation 2 to find the slew rate SR_{ON} required to limit the inrush current I_{INRUSH} for a given load capacitance.

$$SR_{ON} \left(\frac{V}{ms} \right) = \frac{I_{INRUSH}(mA)}{C_{OUT}(\mu F)} \quad (2)$$

For loads requiring a slower rising slew rate, a capacitance C_{dVdt} can be added to the $dVdt$ pin to adjust the rising slew rate and lower the inrush current during turn on. The required C_{dVdt} capacitance to produce a given slew rate can be calculated using Equation 3.

$$C_{dVdt} \text{ (pF)} = \frac{42000}{SR_{ON} \left(\frac{V}{ms} \right)} \tag{3}$$

Use the TPS2595xx design calculation tool, for quick estimation of inrush currents for a given load, input voltage conditions.

5 Test Results

In this section, test waveforms of an eFuse bidirectional power switch for several use cases are presented. The circuit is configured for current limit of 600 mA in both the power path directions and the slew-rate is set at 4.2 V/ms. Following are the parameter values of the circuit and the load:

- Battery voltage, $V_{IN} = 4.2 \text{ V}$
- $R_{ILM} = R_{ILM_1} = R_{ILM_2} = 3.35 \text{ k}\Omega$
- $C_{dVdt} = C_{dVdt_1} = C_{dVdt_2} = 10 \text{ nF}$
- $CL = 100 \mu\text{F}$
- $RL = 100 \Omega$
- X denotes charger is not connected to the system

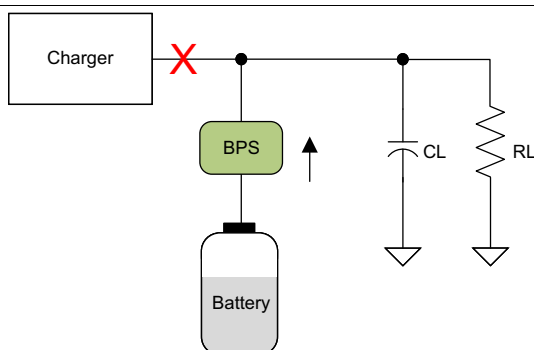


Figure 16. System Start-up From Battery

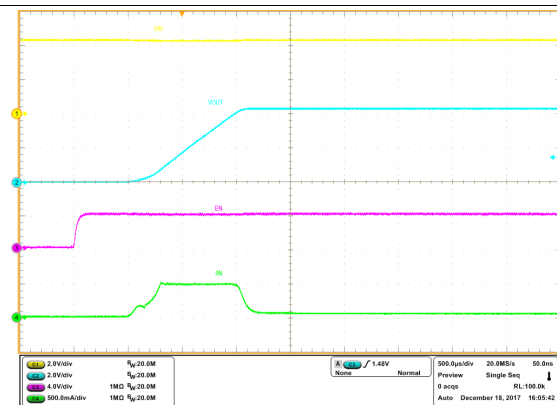


Figure 17. Inrush Current Profile With Load

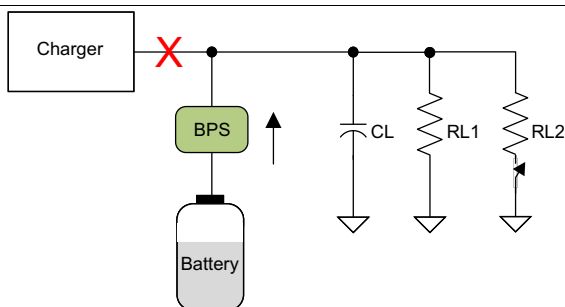


Figure 18. Overload Protection for Battery

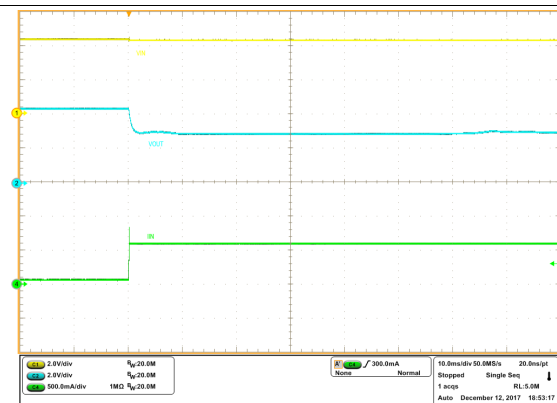


Figure 19. Overload Response of eFuse Solution When Load Resistance is Changed from 100 Ω to 5 Ω

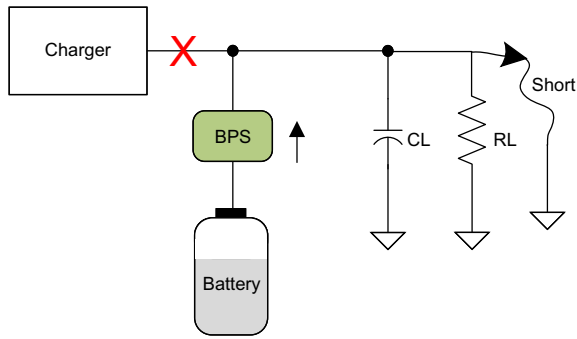


Figure 20. Short-Circuit Protection for Battery

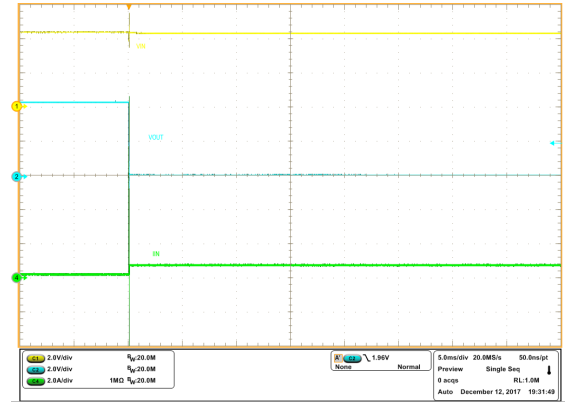


Figure 21. Output Hot Short to GND Response

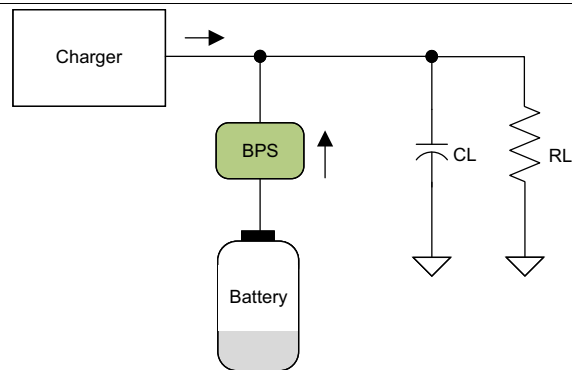


Figure 22. Battery Current During Charger Plug-in Event

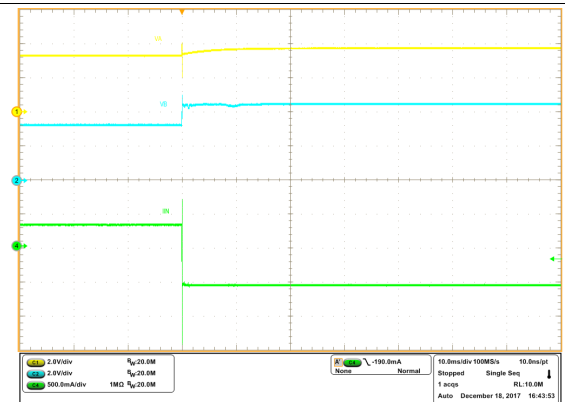


Figure 23. Current Profile of the Battery Path During Charger Plug-In

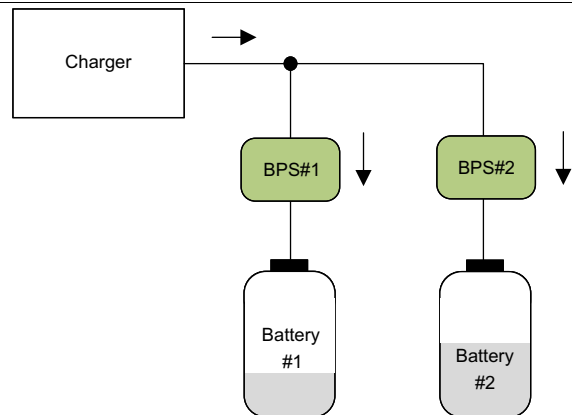


Figure 24. Charger Demultiplexing for Two Batteries

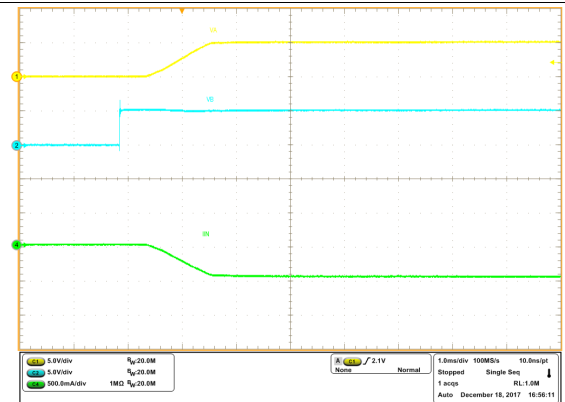


Figure 25. Current Profile of Battery #1, BPS #2 is in Disable Mode

6 Conclusion

The back-to-back connected eFuse configuration offers full functionality as a bidirectional power switch. In addition to the power path control, the integrated protection features in the eFuse solution offers robust power path protection which includes overcurrent limiting, short-circuit protection, and inrush current control. These advantages make an eFuse solution as a favorable option in high-side battery-switching applications.

7 References

1. Texas Instruments, [TPS2595xx, 2.7 V to 18 V, 4-A, 34-mΩ eFuse With Fast Overvoltage Protection Data Sheet](#)
2. Texas Instruments, [TPS2595xx Design Calculation Tool](#)

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Texas Instruments Incorporated ("TI") technical, application or other design advice, services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, "TI Resources") are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using any particular TI Resource in any way, you (individually or, if you are acting on behalf of a company, your company) agree to use it solely for this purpose and subject to the terms of this Notice.

TI's provision of TI Resources does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources.

You understand and agree that you remain responsible for using your independent analysis, evaluation and judgment in designing your applications and that you have full and exclusive responsibility to assure the safety of your applications and compliance of your applications (and of all TI products used in or for your applications) with all applicable regulations, laws and other applicable requirements. You represent that, with respect to your applications, you have all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. You agree that prior to using or distributing any applications that include TI products, you will thoroughly test such applications and the functionality of such TI products as used in such applications. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

You are authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING TI RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY YOU AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

You agree to fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of your non-compliance with the terms and provisions of this Notice.

This Notice applies to TI Resources. Additional terms apply to the use and purchase of certain types of materials, TI products and services. These include; without limitation, TI's standard terms for semiconductor products (<http://www.ti.com/sc/docs/stdterms.htm>), [evaluation modules](#), and [samples](http://www.ti.com/sc/docs/sampterm.htm) (<http://www.ti.com/sc/docs/sampterm.htm>).

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2017, Texas Instruments Incorporated