Reverse Polarity Protection for Embedded Power ICs

Circuit Proposal and Analysis

Embedded Power ICs

About this document

Scope and purpose

This application note proposes an electronic circuit to protect n-channel MOSFET half-bridge based applications with Infineon's Embedded Power ICs. The behavior of the proposed reverse polarity protection circuit is analyzed under certain reverse polarity scenarios, including a dynamic reverse polarity event with a motor as load of the half bridges.

Note: The following information is given as a hint for the design of the circuit only and shall not be regarded as a description or warranty of a certain functionality, condition or quality of the circuit. The responsibility for the circuit lies exclusively with the person who uses or tests it.

Intended audience

This document is intended for customers who are designing a circuit to protect an Embedded Power IC and the half bridges connected to it against negative battery voltages.

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1 Introduction

During the maintenance of a car, the wires connected to the terminals of the battery may be swapped accidentally, causing a negative voltage at the supply of the ECUs of the car. If the ECUs are not designed to withstand a negative voltage at their supply terminals, they could be permanently damaged.

In the particular case of an ECU with n-channel MOSFET half bridges where the drains of the high sides are directly connected to the battery, a reverse polarity event could destroy the MOSFETs. As depicted in ***Figure 1***, when the voltage between “ECU Vbat” and “ECU Gnd” is negative, the parasitic body diodes of the MOSFETs would conduct, providing a path for the current from ground to the battery. Once the maximum body diode continuous forward current or the maximum power dissipation of the MOSFETs are reached or exceeded, they will be damaged.

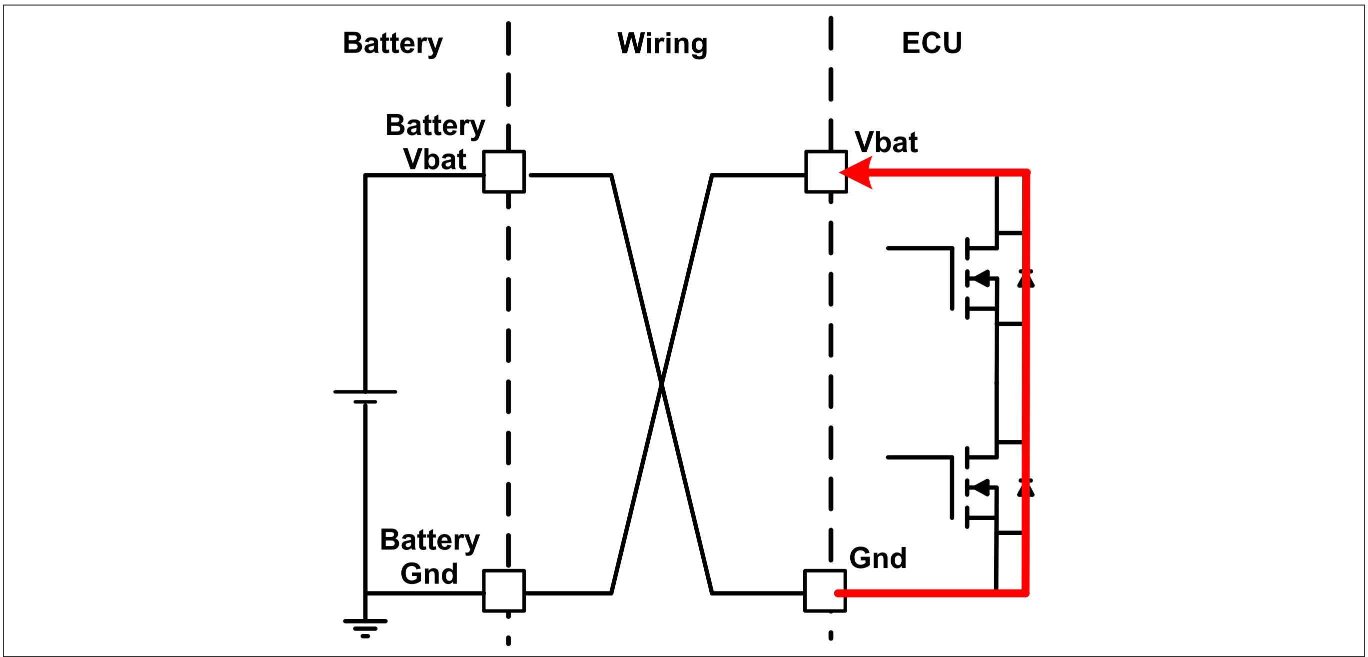

Figure 1 MOSFET half bridge under reverse polarity

In order to prevent this from happening, a reverse polarity protection component should be placed in series to the half bridges. As discussed in *[1]*, a diode, a p-channel MOSFET or an n-channel MOSFET could fulfill this purpose. Every component has advantages and disadvantages. A diode does not need a driver circuit but it causes high power losses due to its large forward voltage drop. A p-channel MOSFET does not require a driver circuit but it has a high on resistance per unit area. Conversely, an n-channel MOSFET has a lower on resistance per unit area, being thus more convenient in terms of power losses and pricing, but it requires a charge pump or a similar driver circuit to boost its gate voltage above the battery voltage to switch on. However, an additional boosting circuit is not needed if an Embedded Power IC *[2]* is already being used in the application, since its charge pump could drive the MOSFET.

This application note focuses on the usage of an n-channel MOSFET as a reverse polarity protection element, together with an Embedded Power IC. First, a circuit is proposed to protect the Embedded Power IC and the half bridges against the reverse polarity. Then, a set of measurements under the LV 124 E-15 supply curves is presented along with an analysis of the circuit’s behavior and finally, conclusions are derived.

2 Proposed Reverse-Polarity Protection Circuit

The application circuit with the reverse polarity protection can be observed in the following figure:

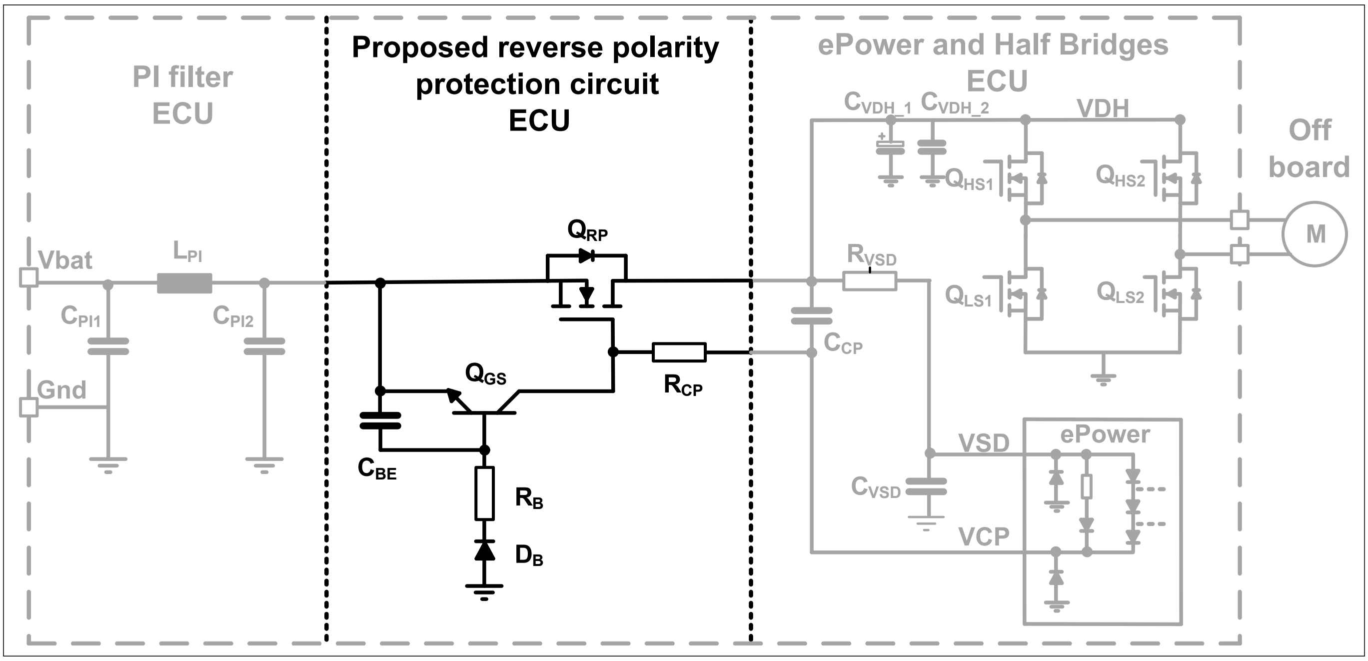

Figure 2 **Proposed reverse polarity protection circuit in the application**

Vbat supplies the whole circuit and represents the connector of the ECU to the car's battery. The PI filter, composed by two capacitors and an inductor, filters out the noise that a PWM-based switching of the half bridges would inject into the supply line of the battery.

Behind the reverse polarity protection circuit, the n-channel half bridges are arranged in a full bridge configuration with a motor as load. The Embedded Power IC's bridge driver and charge pump are supplied by the VSD pin. The latter generates a boosted voltage at VCP, which is used to drive the gate of the reverse polarity protection MOSFET.

However, connecting the gate of the MOSFET to the charge pump pin of the Embedded Power IC would actually prevent the MOSFET from protecting the half bridges. If Vbat became negative, the internal ESD protection diode at VCP would clamp the gate of the MOSFET to ground and the MOSFET's gate-source voltage would be positive. If its gate-source threshold voltage were reached, the MOSFET would conduct and the DC-link voltage VDH would follow the negative Vbat. To prevent this from happening, the MOSFET's gate must be actively discharged and clamped to the battery voltage, i.e. the MOSFET's source. For this purpose, an NPN bipolar transistor can be used together with some passive components, as shown in ***Figure 2***.

The role of each component in the circuit is described in the following table:

Table 1 **Components of the proposed reverse polarity protection circuit and application circuit**

Component	Description
C_{PI1}, C_{PI2}	PI filter capacitors
L_{PI}	PI filter inductor
C_{VDH_1}	DC link buffer capacitors for phase 1 and 2
C_{VDH_2}	Capacitors at phase 1 and 2 for fast current delivery
C_{BE}	Filter capacitor between base and emitter

Table 1 Components of the proposed reverse polarity protection circuit and application circuit (continued)

Component	Description
Q_{GS}	NPN bipolar transistor that discharges the gate of Q_{RP} and clamps it to Vbat when it becomes negative
R_B	Current limiting resistor into the base of Q_{GS}
D_B	Diode that protects the base-to-emitter diode of Q_{GS} from breaking through at the nominal positive battery voltage
Q_{RP}	N-channel MOSFET for reverse polarity protection with its source connected to the pi filter
R_{CP}	Resistor that decouples the gate of Q_{RP} from VCP to allow discharging it and clamping it to the negative Vbat. Notice that VCP is indirectly connected to ground by the ESD protection diode and to VSD inside the Embedded Power IC
Q_{HS1}, Q_{LS1}, Q_{HS2}, Q_{LS2}	N-channel MOSFETs of the half bridge
M	Motor, load of the half bridges
R_{VSD}	Current limiting resistor
C_{VSD}	Capacitive filter for bridge driver and charge pump
C_{CP}	Charge pump storage capacitor

3 Measurements

This section presents the measurements performed at the proposed circuit when the LV 124 E-15 static and dynamic reverse polarity supply curves are applied to the Vbat connector of the ECU at room temperature. These supply curves are part of the LV 124 standard, which defines the test conditions and requirements for electric components in vehicles until 3.5 tons.

In the tests, following signals have been monitored, which correspond to the following channels and colors in the snapshots:

Table 2 Mapping and description of the signals in the snapshots

Signal	Channel	Color	Description
Vbat	C1	Yellow	Voltage at the output of the power supply
Ibat	C2	Pink	Current flowing from the power supply
$V_{GS,QRP}$	C3	Dark blue	Voltage between gate and source of Q_{RP}
$V_{BE,QGS}$	C4	Green	Voltage between base and emitter of Q_{GS}
$V_{DS,QRP}$	C5	Grey	Voltage between drain and source of Q_{RP}
VDH	C6	Purple	Voltage at the drains of the high side MOSFETs (DC link)
VCP	C7	Red	Voltage at VCP pin of the Embedded Power IC
Imotor	C8	Orange	Current flowing to the motor, positive from Q_{HS1} to Q_{LS2}

The signals correspond to following voltage and currents in the circuit:

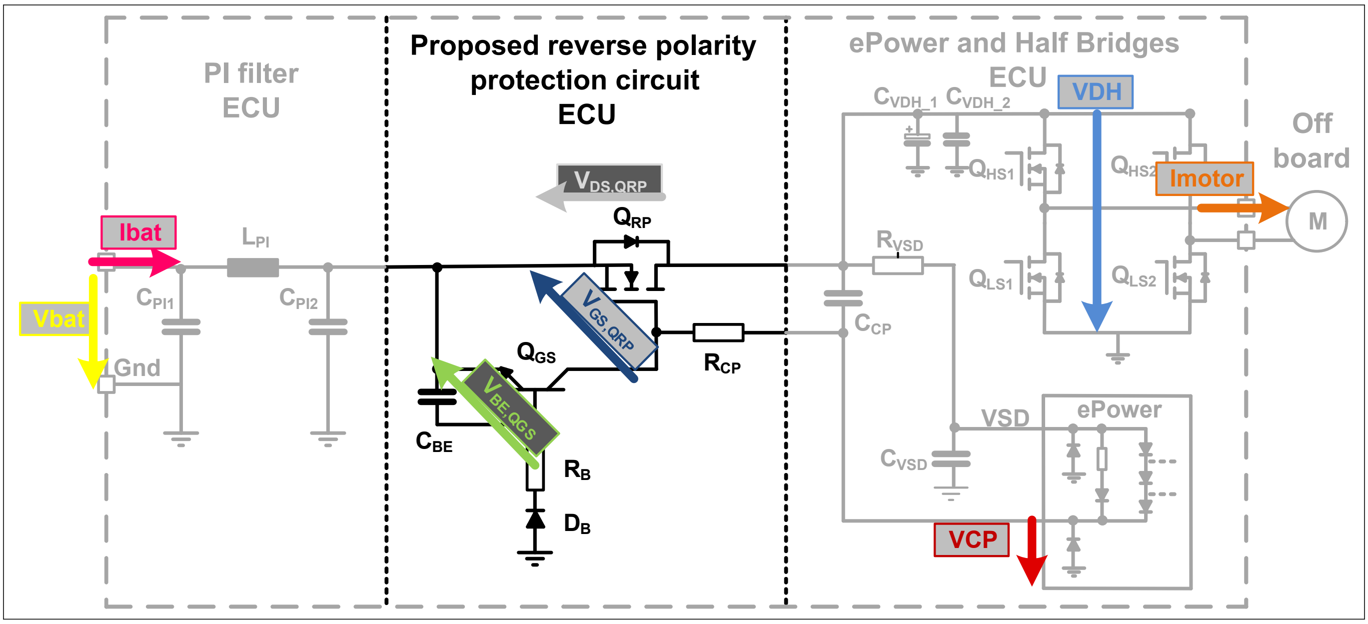

Figure 3 Monitored signals in the proposed reverse polarity protection circuit

3.1 LV 124 E-15 static

In this test, Vbat stays at 0 V for 60 s, decreases to a negative voltage, stays there for 60 s and increases to 0 V again. This cycle is repeated for different negative voltages (from -1 V to -14 V) in steps of 1 V every 120 s. The rising and falling times are 10 ms respectively. During the whole test, Vbat is 0 V or less; thus, the Embedded Power IC is off and it is not driving the MOSFETs.

When this voltage profile is applied at Vbat, the proposed circuit correctly protects the half bridges and the Embedded Power IC from the negative voltages. In the following snapshot of the oscilloscope, it can be observed that VDH does not follow Vbat when it becomes negative. Both VCP and VSD are clamped to ground with the depicted internal diodes inside the Embedded Power IC, which also causes VDH to be clamped.

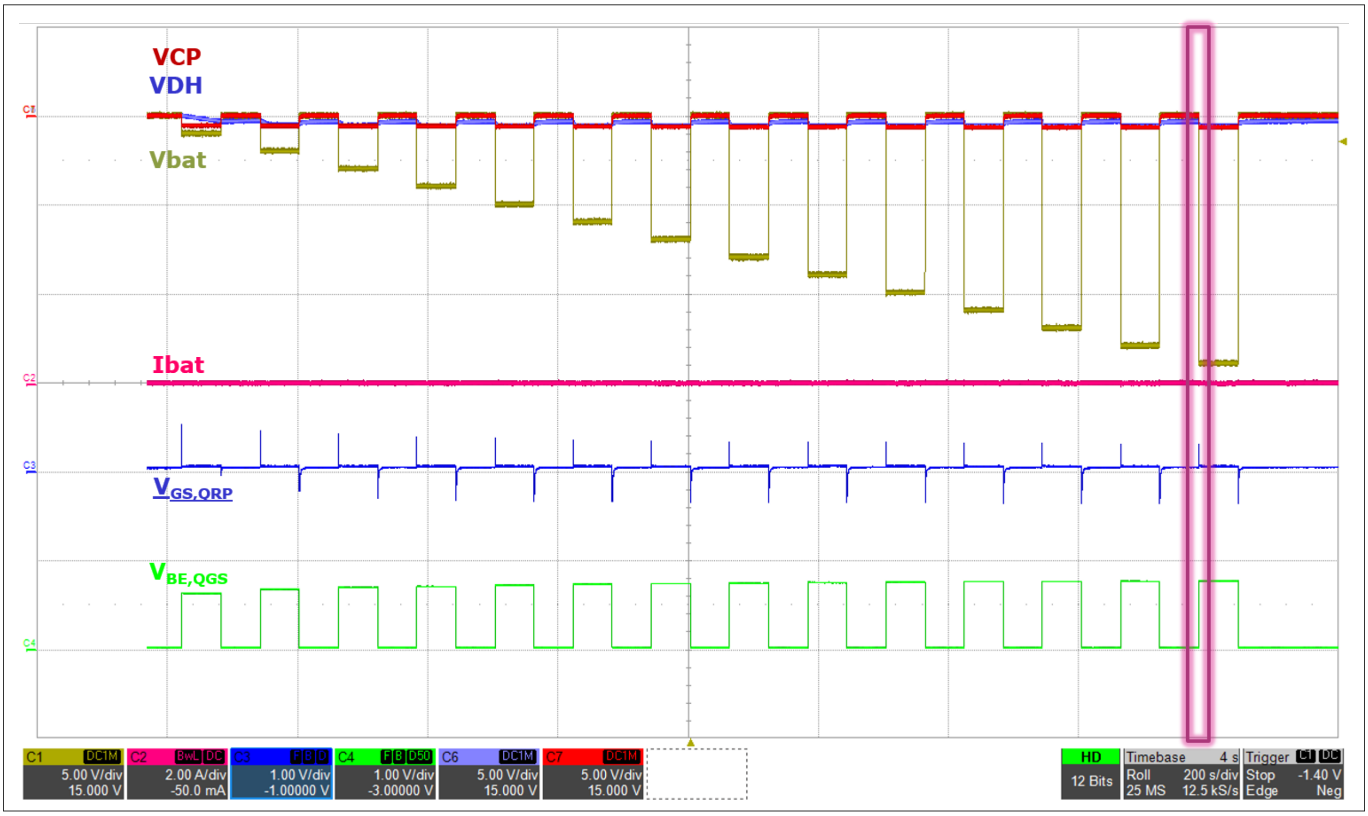

Figure 4 **LV 124 E-15 reverse polarity, static supply curve**

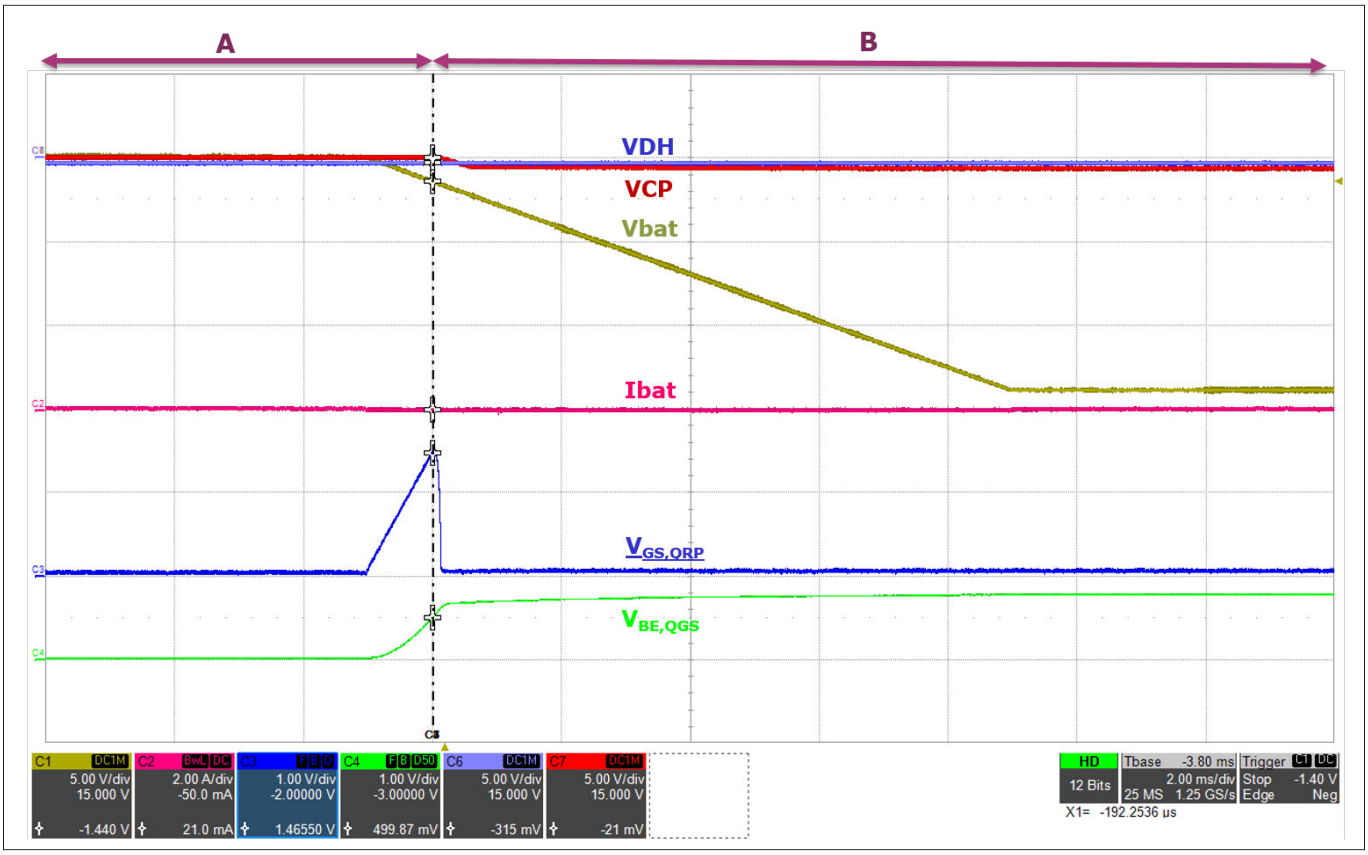

Figure 5 Zoom into *Figure 4*

Two intervals have been marked to explain the behavior of the circuit:

Table 3 Behavior during the intervals shown to *Figure 5*

Interval	Start and end of interval	Q_{GS}	Q_{RP}
A	From Vbat = 0 V to switch off threshold of Q_{GS}	OFF	OFF
B	From switch off threshold of Q_{GS} to Vbat = -14 V	ON	OFF

In interval A, Vbat is not negative enough to forward bias both D_B and the internal D_{BE} of Q_{GS}; so, Q_{GS} stays off. Q_{RP} is also off since V_{GS} is smaller than its $V_{GS(TH),min} \approx 2.2$ V.

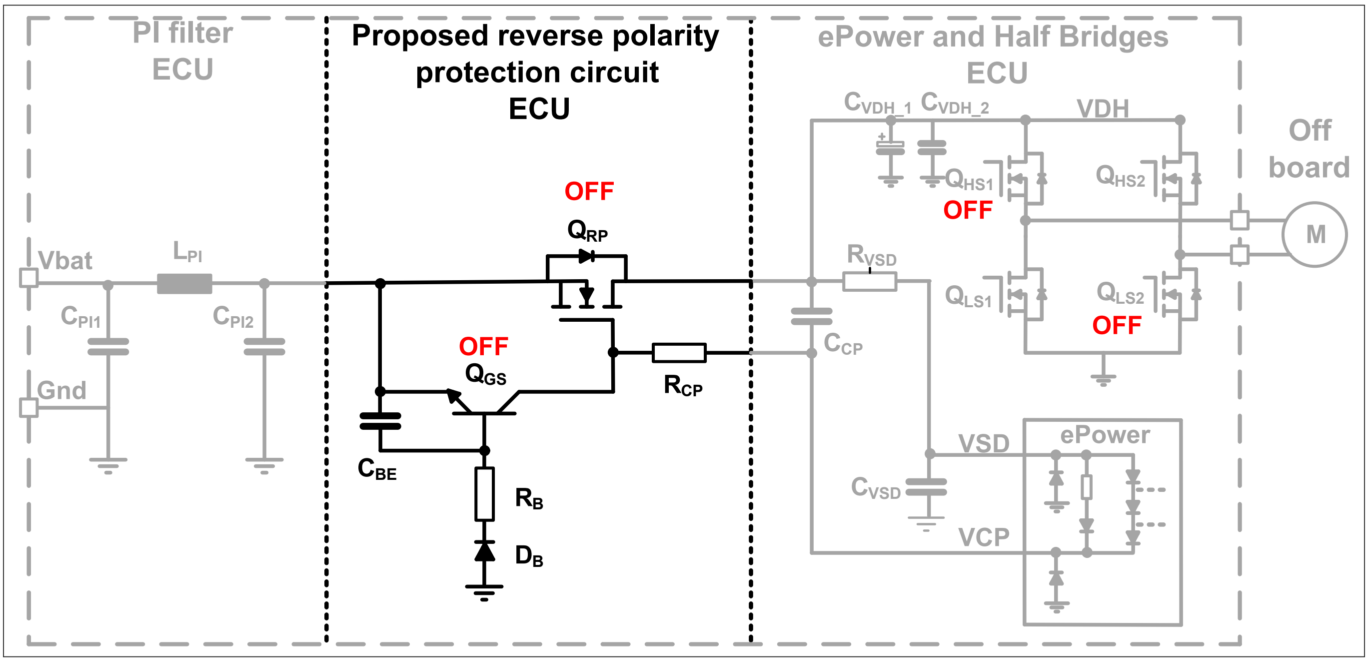

Figure 6 **Component states in interval A of *Figure 5***

At the beginning of interval B, Vbat becomes negative enough to forward bias D_B and the internal D_{BE}, which switches on Q_{GS}. Consequently, V_{GS} of Q_{RP} is clamped to the $V_{CE,SAT}$ of Q_{RP}, which is much smaller than the Q_{RP}'s $V_{GS(TH),min} \approx$ 2.2 V. Hence, Q_{RP} stays off and its body diode does not conduct either, since it is reverse biased. As Q_{GS} is on, R_{CP} is limiting the current that flows from ground over the internal diode at VCP to the power supply; notice in the snapshot that the voltage at VCP is -0.5 V, which corresponds to the forward voltage with opposite sign of this diode.

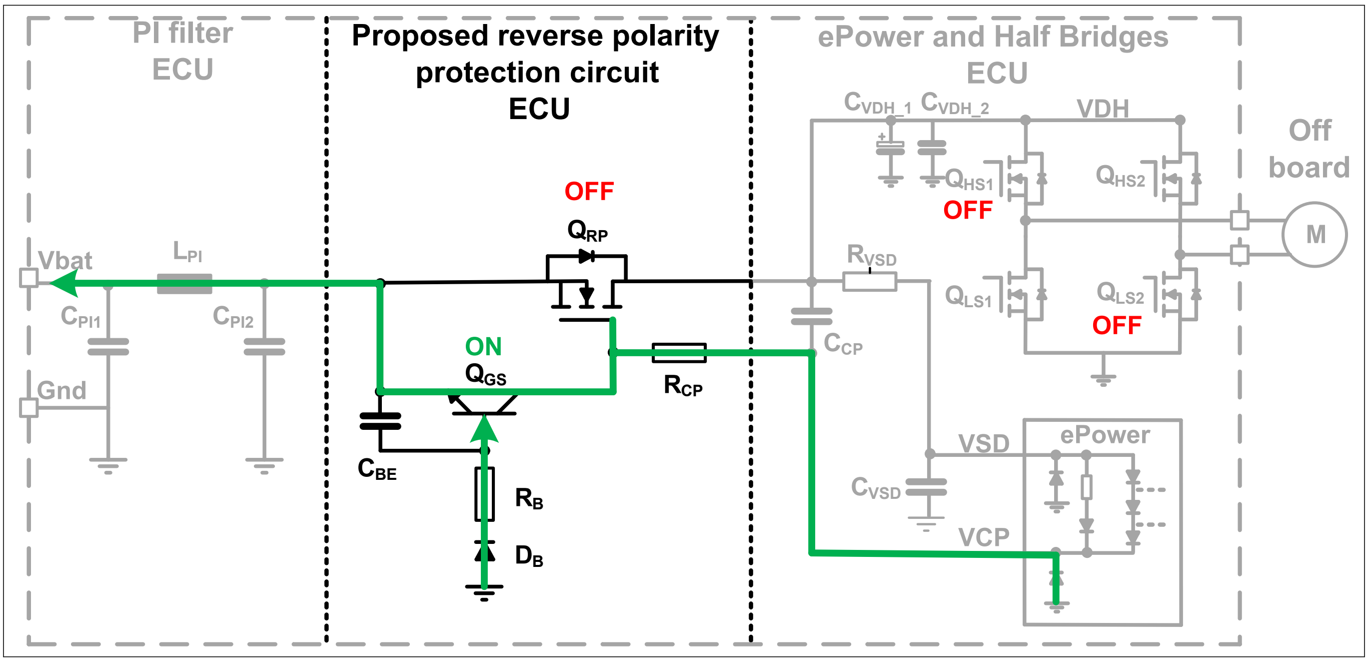

Figure 7 **Component states and current flows in interval B of *Figure 5***

3.2 LV 124 E-15 dynamic

In contrast to the previous test, Vbat starts from a voltage of 10.8 V and remains at this voltage for 60 s, so the Embedded Power IC is on and it is driving the MOSFETs. After 60 s, Vbat decreases and stays at -4 V for 60 s and increases to 10.8 V again. This cycle is repeated three times with a rising and falling time of 10 ms.

This voltage profile has been applied to the circuit with and without an operating load at the half bridges.

3.2.1 Without operating load at the half bridges

Unlike in the previous tests, the Embedded Power IC is supplied within its functional range before the supply voltage becomes negative. Therefore, VCP is providing a boosted voltage of VSD + 15 V, which is being used to drive the gate of Q_{RP}. In this test, the bridge driver is off and no current flows from Q_{HS1} to Q_{LS2}.

Under the dynamic LV 124 E-15, the proposed circuit also correctly protects VDH from the negative voltage; the following figure shows that this voltage is clamped by the Embedded Power IC's internal diode and do not follow the negative Vbat:

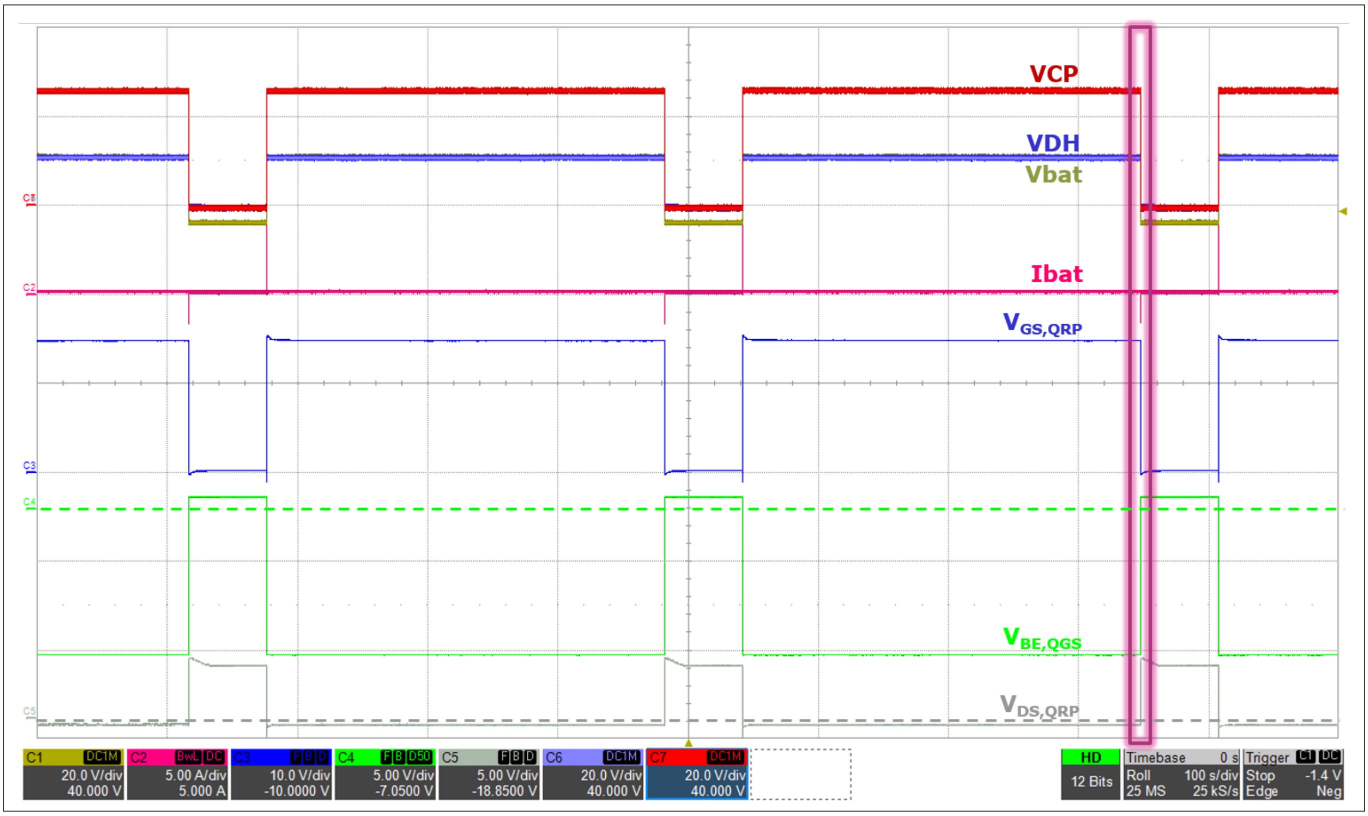

Figure 8 LV 124 E-15 reverse polarity, dynamic supply curve without operating load at half bridges

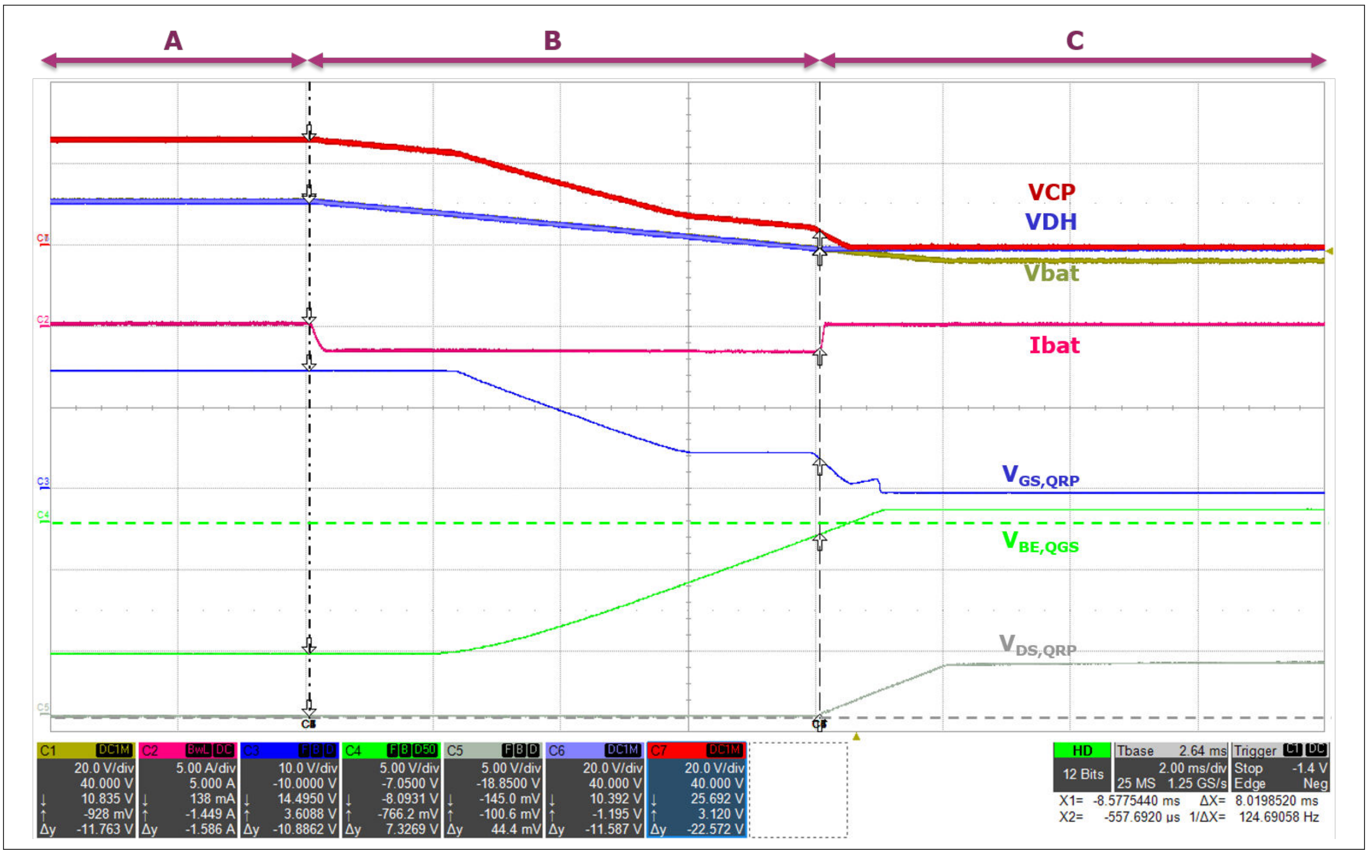

Figure 9 **Zoom into *Figure 8***

Three intervals are considered to explain the behavior:

Table 4 **Behavior during the intervals shown in *Figure 9***

Interval	Start and end of interval	Q_{GS}	Q_{RP}
A	From Vbat = 10.8 V to start of Vbat decrease	OFF	ON
B	From start of Vbat decrease to switch off threshold of Q_{RP}	OFF	ON
C	From switch off threshold of Q_{RP} to Vbat = -4 V	OFF->ON	OFF

During the interval A, the charge pump of the Embedded Power IC is on and boosting the gate of Q_{RP}. The DC link capacitors C_{VDH_1} are already charged to a voltage close to Vbat at this point in time.

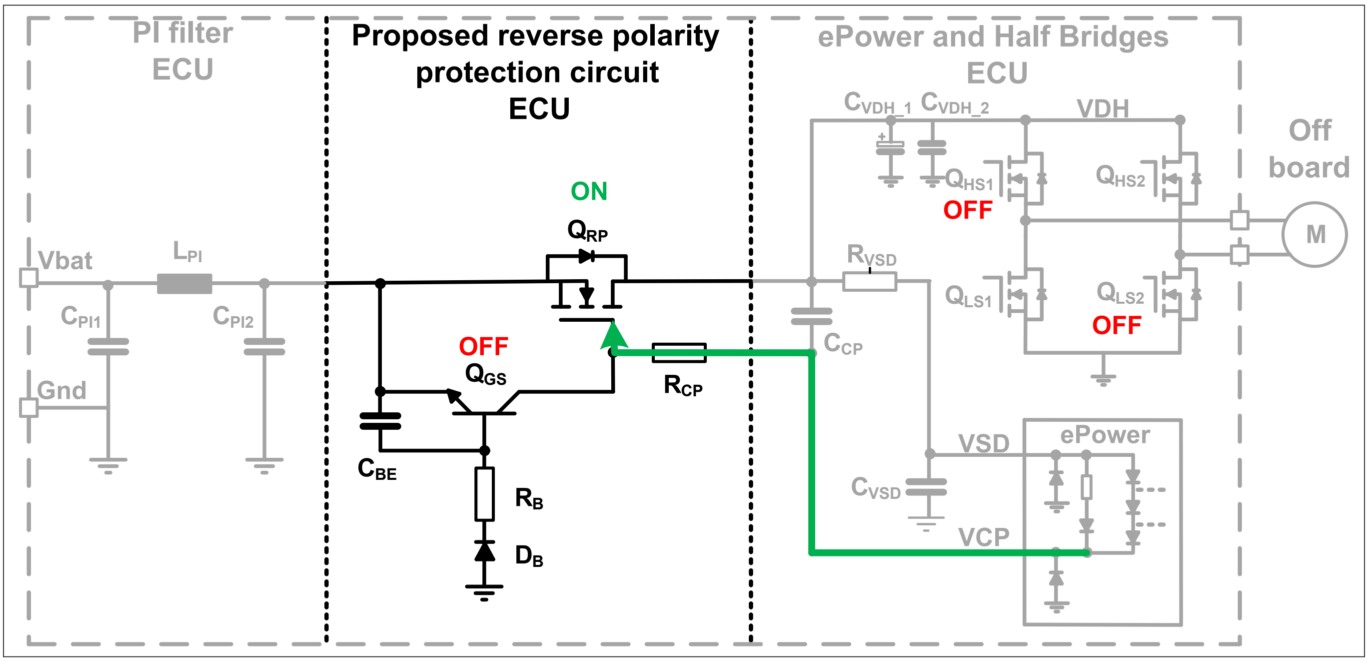

Figure 10 **Component states and current flows in interval A of *Figure 9***

When Vbat drops in interval B, the DC link capacitors discharge and the power supply sinks this current (negative Ibat). This current flows from drain to source of Q_{RP}, since VCP still boosts the gate over $V_{GS(TH),max} \approx 3.8$ V.

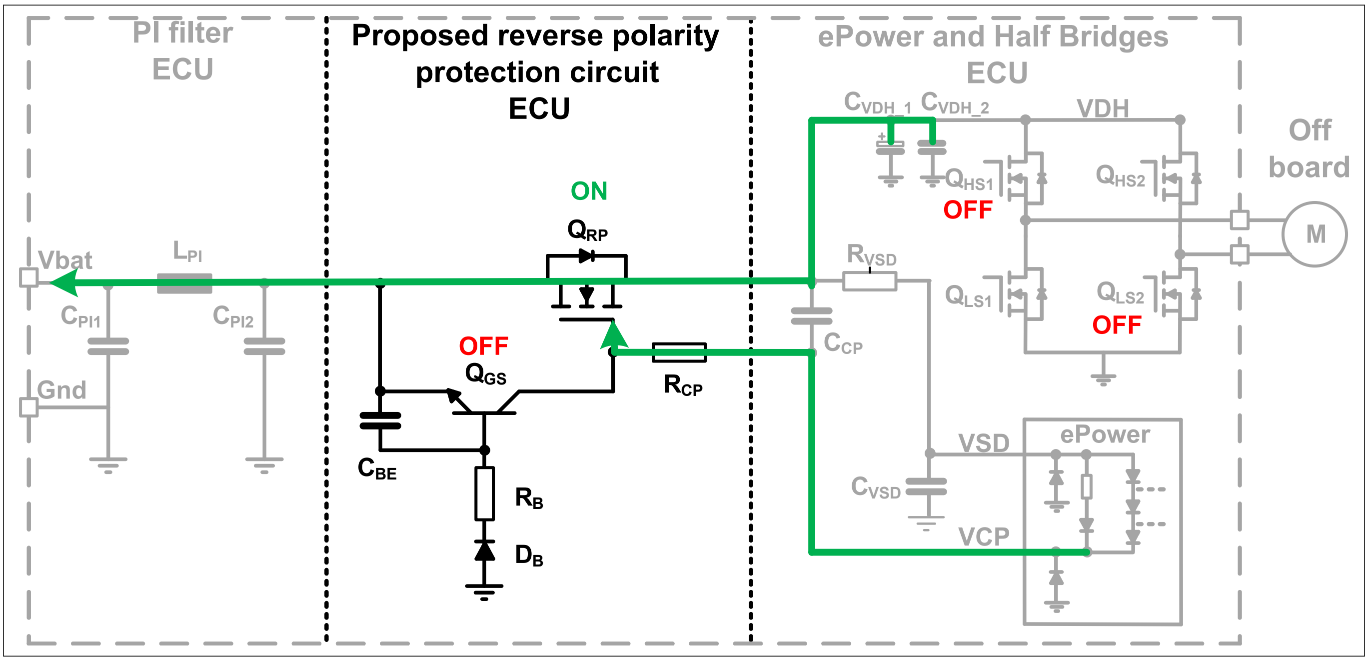

Figure 11 **Component states and current flows in interval B of *Figure 9***

Q_{RP} switches off at the beginning of interval C, when $V_{GS(TH)} \approx 3.6$ V is reached. As the current cannot flow from VDH to Vbat any longer, Ibat decreases. Then, when Vbat becomes negative enough to forward bias D_B and the internal D_{BE}, Q_{GS} switches on.

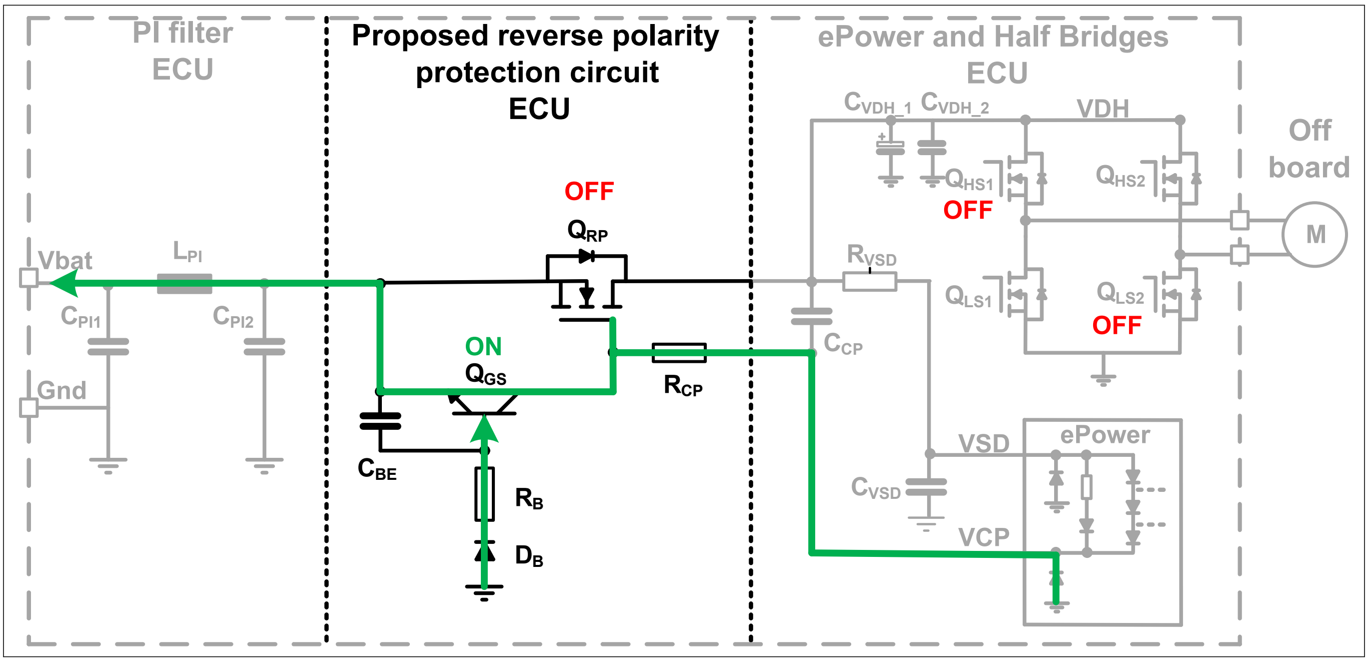

Figure 12 **Component states and current flows in interval C of *Figure 9***

3.2.2 With operating load at the half bridges

In this test, the Embedded Power IC is also supplied with 10.8 V for 60 seconds. The bridge driver switches on Q_{HS1} and Q_{LS2}, so the measured Imotor is considered as positive when it flows from Q_{HS1} to Q_{LS2}. Due to the large inertia of the selected motor, a 200W air blower from a car heating system, the motor will work in generator mode when the battery voltage becomes negative, injecting current into the battery over Q_{RP} just before it is switched off. In this test, it can be also observed that VDH is correctly protected from the negative voltage at Vbat and that the circuit successfully resumes operation when Vbat goes back again to 10.8 V:

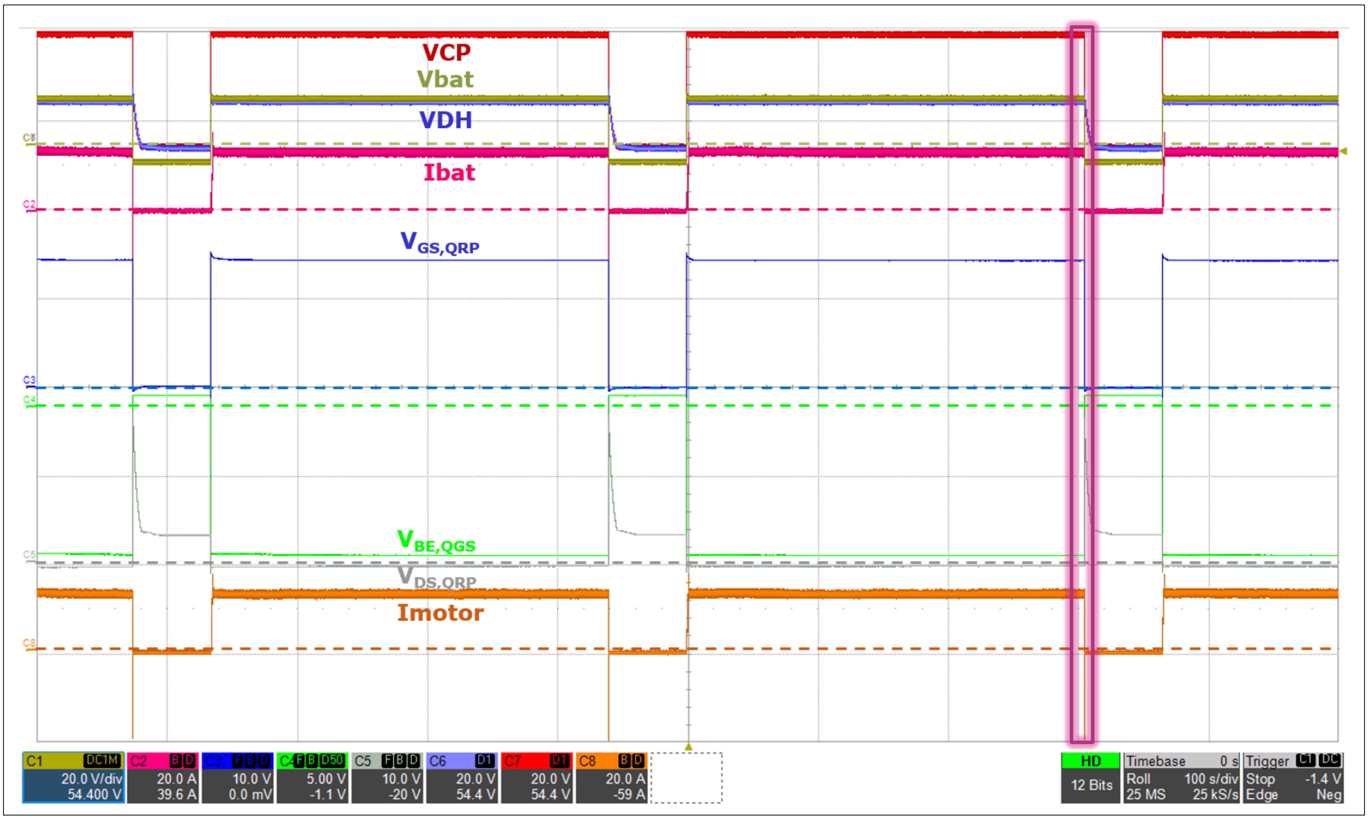

Figure 13 LV 124 E-15 reverse polarity, dynamic supply curve with operating load

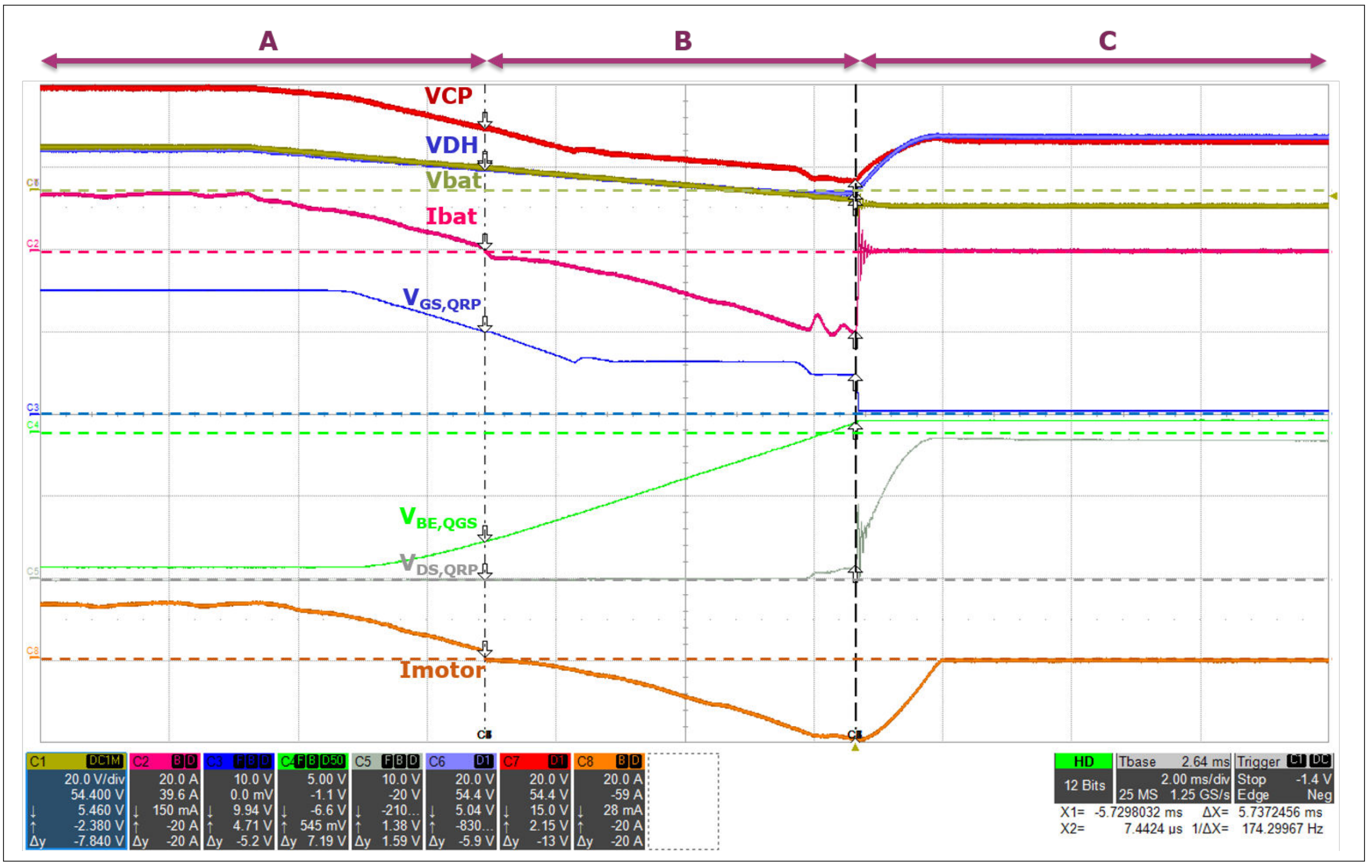

Figure 14 Zoom into *Figure 13*

The behavior of the circuit will be explained for each of the following intervals:

Table 5 Behavior during the intervals shown in *Figure 14*

Interval	Start and end of interval	Bridge driver	Q_{GS}	Q_{RP}
A	From Vbat = 10.8 V to switch off threshold of bridge driver	ON	OFF	ON
B	From switch off threshold of bridge driver to switch off threshold of Q_{GS}	OFF	OFF	ON
C	From switch off threshold of Q_{GS} to Vbat = -4 V	OFF	ON	OFF

In interval A, the Embedded Power IC drives Q_{RP}, Q_{HS1} and Q_{LS2} and the motor is spinning. Hence, the current flows from the battery to the motor over Q_{RP} and Q_{HS1} and returns to ground over Q_{LS2}:

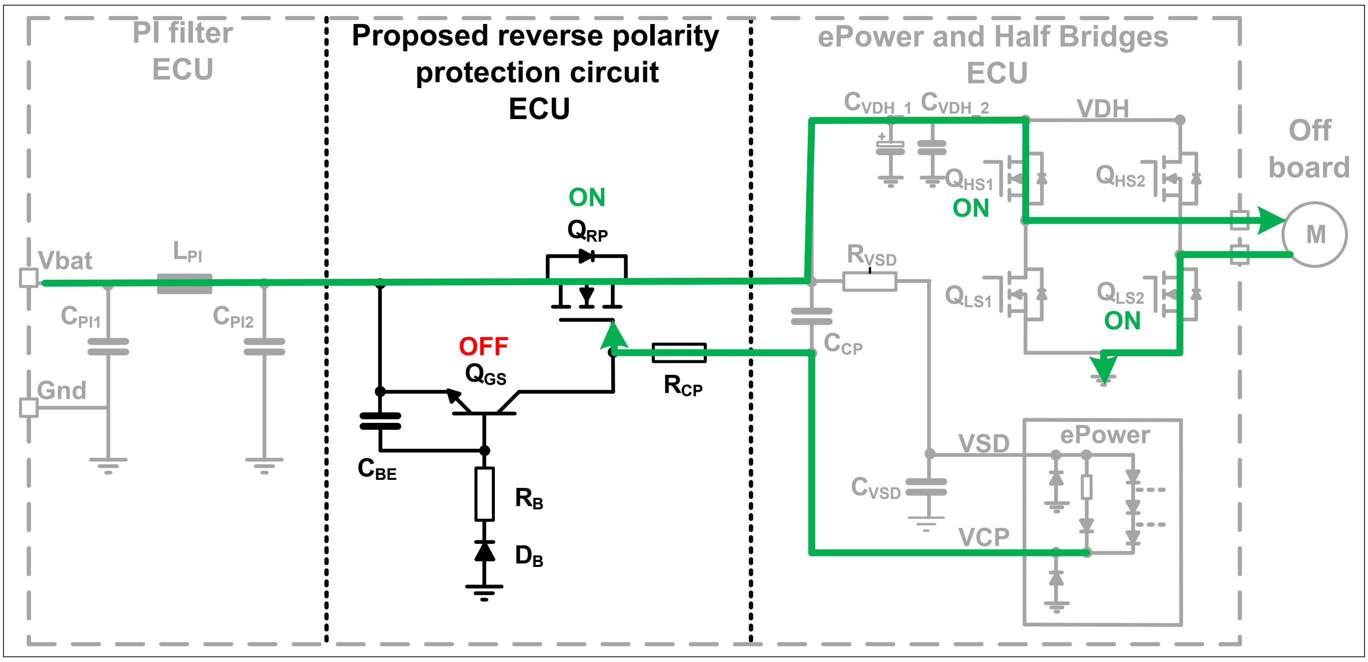

Figure 15 Component states and current flows in interval A of *Figure 14*

At the beginning of interval B, the Embedded Power IC switches off its gate driver, since the undervoltage threshold at VSD is reached. At this point, the current through the motor crosses zero and it becomes negative. The motor is now working as a generator, since it continues spinning due to its high inertia. This current flows from the motor into the power supply over the body diodes of Q_{LS2} and Q_{HS1} and drain-source channel of Q_{RP}. Notice that at the end of interval B, the DC link capacitors have already been fully discharged.

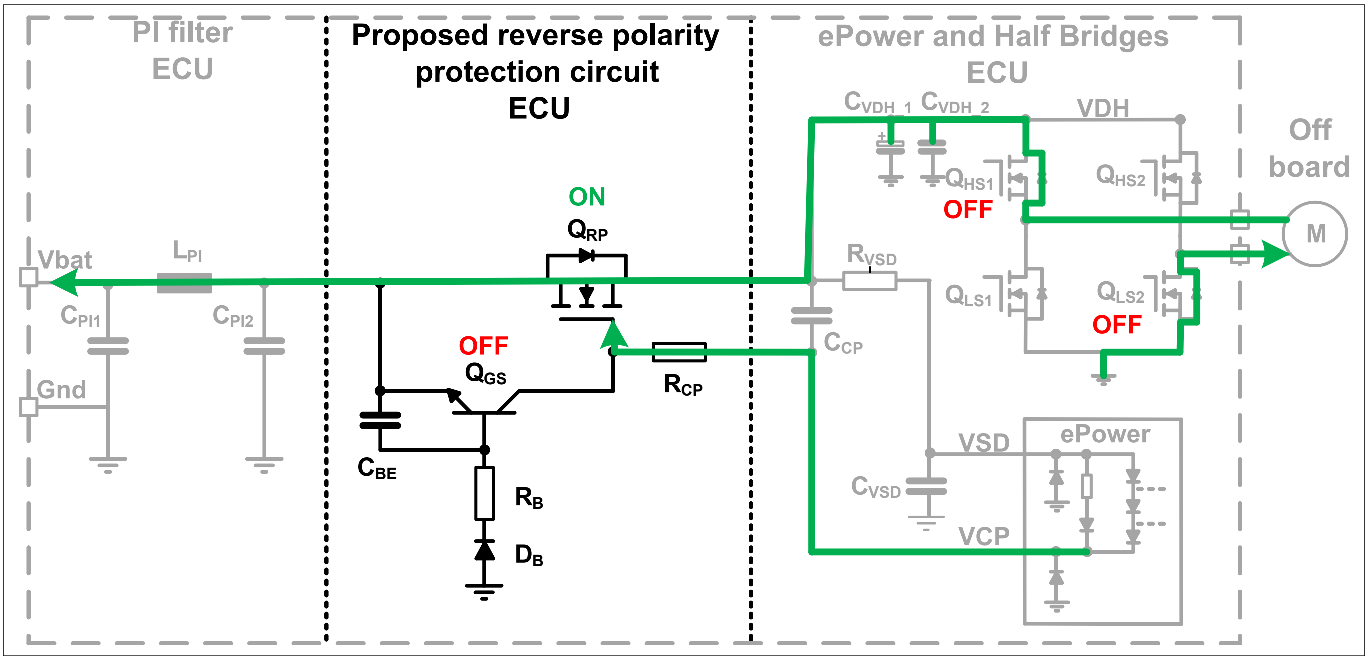

Figure 16 Component states and current flows in interval B of *Figure 14*

At the beginning of interval C, Vbat has decreased enough to forward bias D_B and the NPN's internal diode D_{BE}, so Q_{GS} starts conducting and fully discharges the gate of Q_{RP} towards Vbat. This causes a large dI/dt from -20 A to 0 A at the inductor of the PI filter which is visible at Ibat and $V_{DS,QRP}$ (notice that there are no overshoots in the test of the previous section without operating load). The filtering capacitor C_{BE} prevents Q_{GS} from toggling when Q_{GS} switches on. As the current from the motor cannot flow to the power supply any more, it charges the DC link

capacitors and the voltage at VDH increases. They are charged until the current delivered by the motor decreases to 0 A.

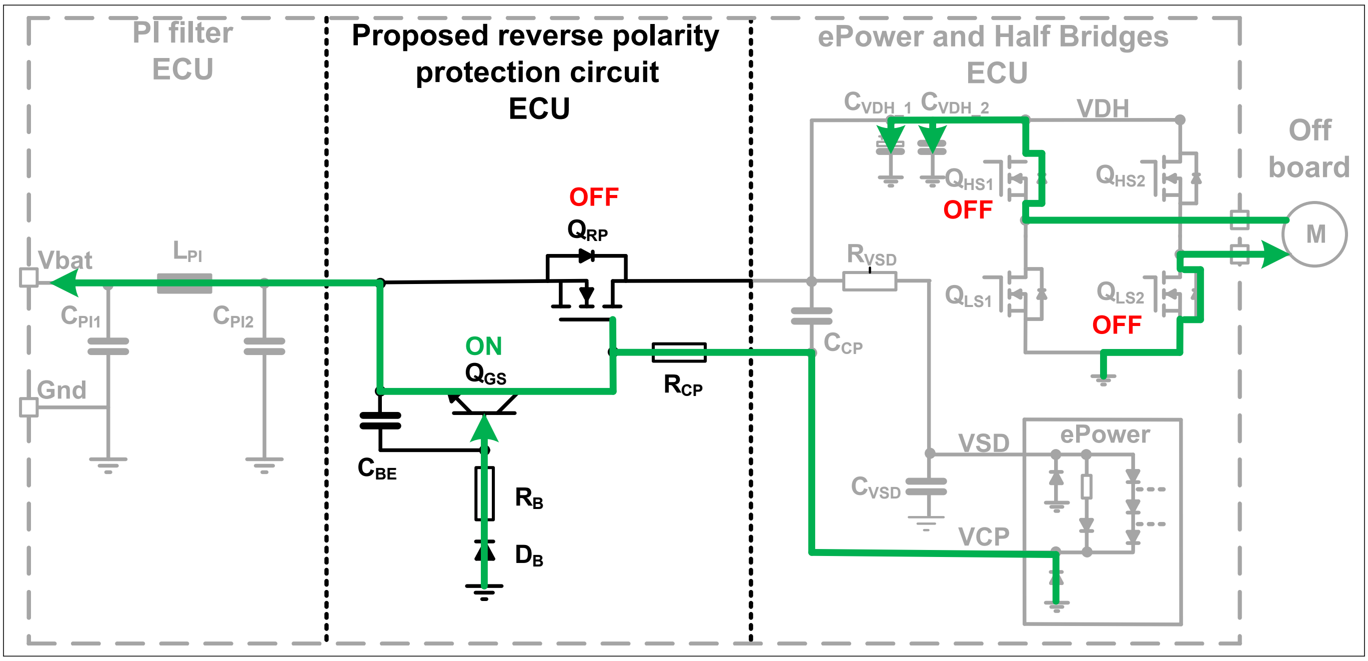

Figure 17 **Component states and current flows in interval C of *Figure 14***

4 Conclusion

The evaluated reverse polarity protection circuit is a suitable proposal for MOSFET driven motor applications with an Embedded Power IC. Its functionality under the LV124 E-15 supply curves has been verified with limited conditions, e.g. temperature dependencies, aging and parameter deviations are not covered by these results. The circuit must be evaluated in the customer application individually.

5 Bibliography

[1] Pürschel, M, 2009: "Application note: automotive MOSFETs, reverse battery protection". Infineon Technologies AG

[2] Infineon Technologies AG, 2018: „Embedded power ICs", retrieved from ***https://www.infineon.com/cms/en/product/microcontroller/embedded-power-ics-system-on-chip-/***

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