Technical White Paper

Isolated Bias Power Supply Architecture for HEV/EV Single Stage Onboard Chargers

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ABSTRACT

Single-stage topology is currently emerging as the preferred choice for onboard chargers (OBCs) in electric vehicles (EVs) by demonstrating a higher power density, a smaller size, and potentially lower costs when compared to traditional, dual-stage OBCs with PFC (power factor correction) and DC-DC converter stages. The matrix converter is generally the most popular topology for single-stage OBCs. In the OBCs design, the isolated bias power supply contains a major part of the circuit, which is primarily used to supply the required power to the gate drivers. This paper proposes architectures that offer efficient, isolated bias power supplies especially focused on single-stage OBCs. There are several architectures available to gate drivers in a single-stage onboard charger which incorporate an isolated bias power supply. These architectures also directly influence the choice of topologies, and related devices used, for the isolated bias power supply in the single-stage onboard charger.

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Trademarks

1 Introduction

An isolated bias supply provides power to the different gate-drivers in HEVs and EVs. There are different topologies to design an isolated bias power supply. Generally, the most commonly used topologies are flyback, push-pull, LLC-resonant, and integrated transformer modules. Each topology provides specific advantages, but at the same time, has tradeoffs and challenges. The choice of the topology depends largely on the overall architecture of the isolated bias power supply. Different Si, SiC, GaN, IGBT switches (and possibly others) require different input voltage ranges for gate-to-source voltage (V_{GS}). Therefore, the architecture of the isolated bias power supply, and the selection of devices, also depend on the switches used in the design.

Isolated bias power supplies either take power from the low-voltage battery or from the high-voltage battery of the HEV or EV. Based on the power source, isolated bias power supplies can be divided into two groups: low-voltage isolated bias power supplies and high-voltage isolated bias power supplies. The isolated bias supply circuit can be directly connected to the battery or connected to the battery using preregulators. The required preregulators depend on the wide input voltage range capability of the device. Although low-voltage batteries are commonly the power source for isolated bias power supplies, occasionally, both low-voltage and high-voltage batteries provide redundancy in the system. A redundant power supply can assist in meeting the requirements of a higher functional safety rating for the overall system.

The matrix converter is generally the most popular topology for single-stage OBCs. Therefore, this paper mainly focuses on the architecture of a matrix-converter isolated bias power supply. Figure 1-1 shows a single-stage OBC featuring a generic matrix-converter with AC as the primary-side and high voltage DC side stages. The switches are named HS_1, LS_1, HS Bias, LS Bias, SW1, SW2, SW3, and N (neutral) in different colored boxes. The colored boxes indicate that the gate driver of the switches in the same box can be shared from the same output of the isolated bias power supply since these switches have the same reference for V_{GS}. The same nomenclature for the gate driver of each of these switches and the isolated bias power supply to the gate drivers can be considered in the same manner. The figures in this document use this nomenclature to describe the different architectures of the different isolated bias power supplies.

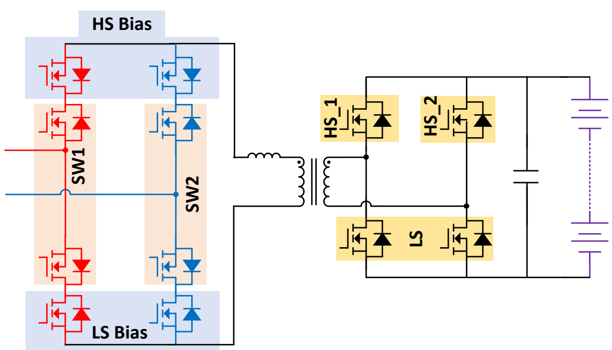

Figure 1-1. Single-Phase Topology (Common-Drain)

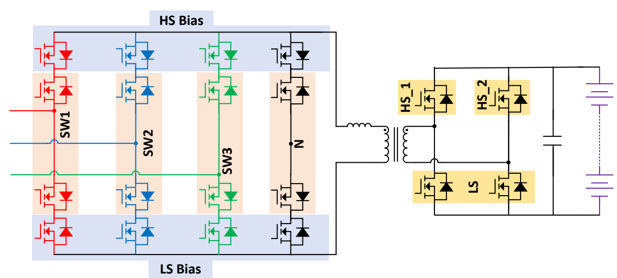

Figure 1-2. Three-Phase Topology (Common-Drain)

The power requirement from the isolated bias supply to each single-channel isolated gate driver, or one channel of a dual-channel isolated gate driver, can be calculated using Equation 1. The power requirement can vary depending on the switching frequency, gate charge of the switches driven by the isolated gate driver, gate-to-source voltage of the switch, and so forth. If the isolated bias output is used to supply power to multiple isolated gate drivers, then the total required power output from the isolated bias power supply sums up. For example, if the bias supply output is powering four single-channel isolated gate drivers, then the total power requirement is four times the calculated P_{reqd} using Equation 1.

$$P_{reqd} = V_{GS} \times Q_g \times f_{sw} + V_{DD} \times I_{DD} \tag{1}$$

1.1 Low-Voltage Isolated Bias Power Supply

Low-voltage bias power supply circuits usually have a 12V battery as a power source in HEVs and EVs. Although there are some systems with 48V as a low-voltage battery, this paper focuses on the 12V battery system. However, these architectures are still relevant for 48V low-voltage battery designs. For example, in a 48V low-voltage battery design, one use-case is to use a converter to lower the voltage from 48V to 24V, 15V, or 12V to use the same isolated bias power devices as a 12V battery. Alternatively, another use-case is to have isolated bias power devices supporting an input voltage range designed for a 48V battery.

Considering the state of charge (SOC) of the 12V low-voltage battery, the wider input voltage range needs to be supported by the isolated bias power supply (for example: 8V–16V). In cold crank and load dump scenarios, the range requirement of the input voltage goes further down or further up, respectively. There can be differences in the wide input voltage range of a 12V low-voltage battery depending on the OEM. Not all types of topologies, and the associated devices, can support this wide input voltage range. Therefore, in several designs, a preregulator is necessary between the low-voltage battery and the isolated bias power supply to regulate the input voltage for the isolated bias power supply device.

Table 1-1. Texas Instruments' Low-Voltage Isolated Bias Supply Topologies and Associated Devices

Parameters	Open-Loop LLC	Push-Pull	Primary-Side-Regulated Flyback	Fully-Integrated Modules (Full Bridge + Transformer)
V_{IN} Minimum and Maximum	9V, 34V	3V, 36V(1)	4.5V, 65V(1)	4.5V, 26.4V(1)
P_{OUT} Maximum	Up to 9W	Up to 7.5W(1)	Up to 30W(1)	Up to 2.5W(1)
V_{OUT} Regulation	Unregulated	Unregulated, V_{IN} controlled	Regulated	Regulated
Switching Frequency	0.1–1.2MHz	0.1–2MHz	20–350kHz	11–15MHz
Isolation	Depends on the transformer used			Up to 5kV, basic or reinforced
Supporting Devices	UCC25800-Q1	SN6501-Q1 SN6505-Q1 SN6507-Q1	LM518x-Q1 LM2518x-Q1 LM515x-Q1 LM34xxx-Q1	UCC1413x-Q1 UCC1414x-Q1 UCC1424x-Q1 UCC1524x-Q1 UCC34141-Q1 UCC35131-Q1
Advantages	High efficiency Low EMI High CMTI	Wide V_{in} range High line regulation	High efficiency Wide V_{in} range High load and line regulation	No external transformer Robustness to vibration Small size and low height
Challenges	Requirement of preregulator	Low efficiency at low I_{out} (<50mA)	Parasitic capacitance across isolation barrier of flyback transformer	Low efficiency Power limitation

(1) Depends on the variant of the device.

1.2 High-Voltage Bias Power Supply

High-voltage bias power supply circuits have a high-voltage battery as a power source in HEVs and EVs. As a high-voltage battery, 400V and 800V voltage batteries are generally the most common battery in EVs. The isolated bias supply connected to the high-voltage battery needs to support a wider input voltage range. The range of wide input voltage requirements for HV batteries is similar to the range of wide input voltage requirements for LV batteries for different SoC and load dump scenarios. Based on the SoC of the battery, a wider input voltage range must be supported. For example, the voltage ranges of 240V–450V are commonly considered for a 400V battery and 550V–950V are commonly considered for an 800V battery. However, this voltage range can be different depending on the OEM requirement.

Although the high-voltage battery can be used as a primary source for the isolated bias power supply, the battery is mostly used to provide redundancy. Flyback topology is usually selected for such a high and wide input voltage range from a technical perspective and with regard to potentially minimizing costs.

Table 1-2. Texas Instruments High-Voltage Isolated Bias Supply Topologies and Associated Devices

Device	UCC28C56H-Q1	UCC28700-Q1	UCC28740-Q1 UCC28730-Q1	UCC28781-Q1
Switching Type	Hard-switched	Valley switching	Valley switching	Zero-voltage switching (ZVS)
Feedback Regulation(1)	Primary | Secondary (Optoemulator)	Primary	Primary | Secondary (Optoemulator)	Secondary (Optoemulator)
Integrated High-Voltage Start-Up	No	No	Yes	No
Typical Power Levels	20W–100W	2W–65W	2W–65W	50W–150W
Topology	Flyback	Flyback	Flyback	Flyback

Table 1-2. Texas Instruments High-Voltage Isolated Bias Supply Topologies and Associated Devices (continued)

Device	UCC28C56H-Q1	UCC28700-Q1	UCC28740-Q1 UCC28730-Q1	UCC28781-Q1
Design Resource	UCC28C56EVM-066	N/A	PMP23431 | PMP41009	UCC28781EVM-053

(1) Primary-side regulation removes the optoemulator from the design.

2 Bias Power in Common-Source Configuration of Back-to-Back FETs

Figure 2-1 shows the back-to-back FETs in a common-source configuration. The common-source configuration requires a total of eleven isolated bias power supply outputs, which includes eight in the AC side and three in the HV battery side. The back-to-back switches in the AC side with a common-source configuration can share the same isolated bias power supply output. In a common-source single-stage OBC configuration, the isolated bias power supply is similar to the dual-stage OBCs with some differences. For example, there is no primary DC side in single-stage OBCs and no low-side switches sharing the same bias power supply output. Refer to the *Isolated Bias Power Supply Architecture for HEV and EV Onboard Chargers* technical white paper for a detailed description of an isolated bias power supply architecture for dual-stage OBCs with PFC and DC-DC stages.

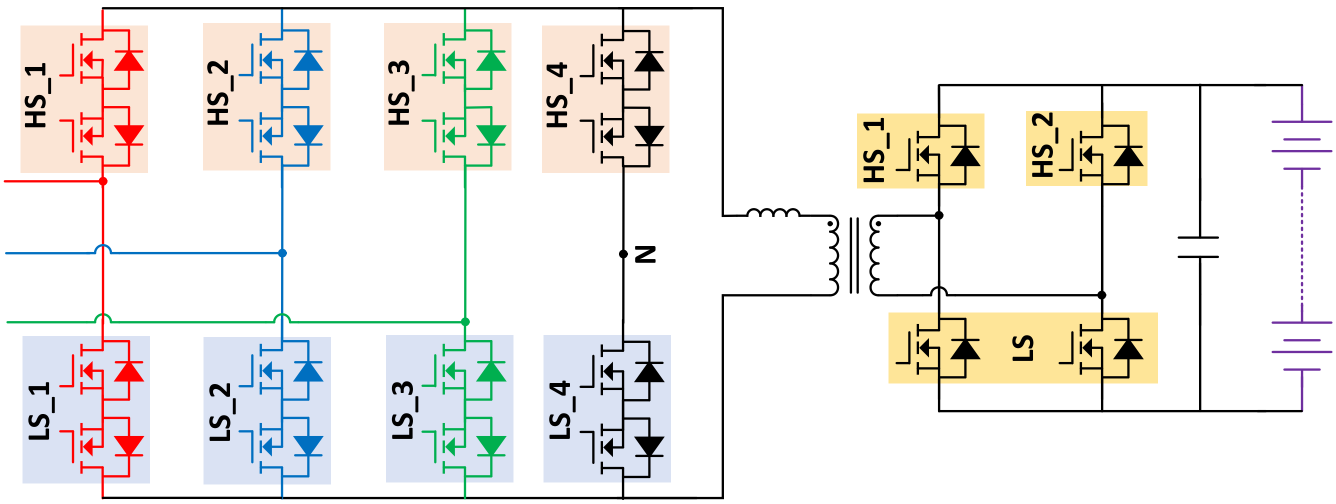

Figure 2-1. Block Diagram of the 3-Phase Single-Stage OBC With Common-Source Configuration

3 Bias Power in Common Drain Configuration of Back-to-Back and Bidirectional FETs

The common drain configuration of back-to-back FETs and bidirectional switches affects the architecture of the isolated bias power supply on the primary side of single-stage OBCs immensely. The switches do not have a common source, therefore, supplying both FETs using the same isolated bias power output is not possible. In the bidirectional switches, two FETs inside a single package can be driven independently using two single-channel gate drivers or a dual-channel gate driver. Therefore, two different isolated bias power supplies are needed for the bidirectional switch. In Figure 3-1, the same color shaded FETs can share the same isolated bias power supply output.

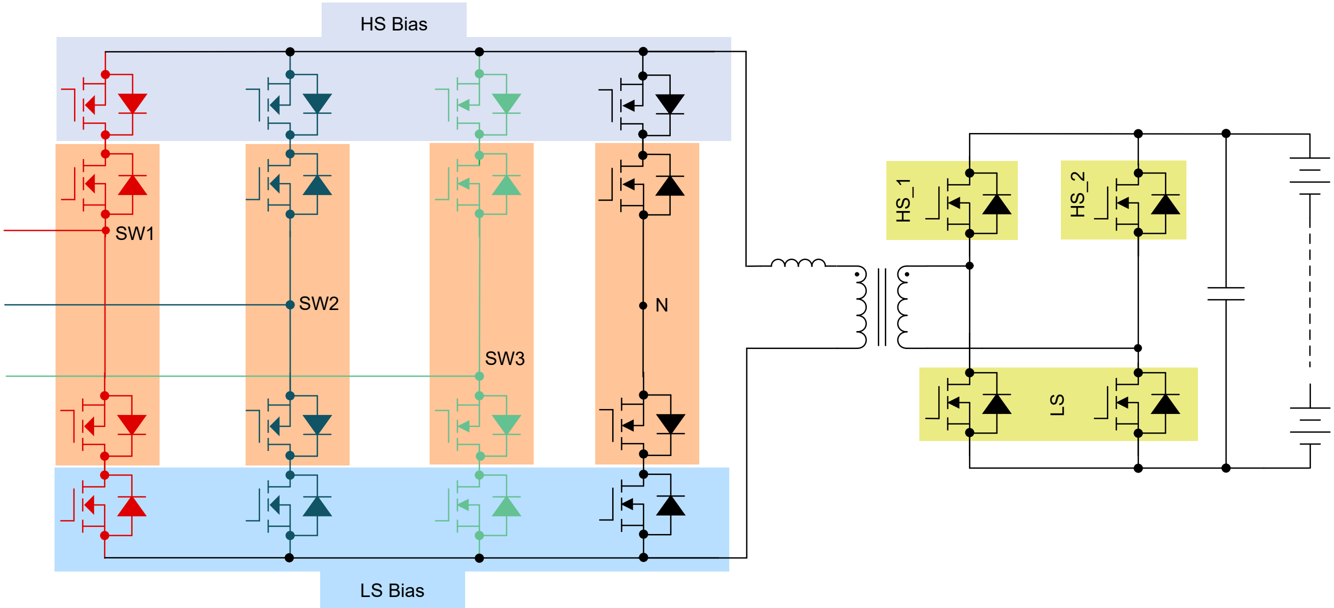

Figure 3-1. Block Diagram of the 3-Phase Single-Stage OBC With Common-Drain Configuration

There are a total of nine isolated bias power supply outputs required in the common-drain configuration, which includes six in the AC side and three in the HV battery side. The top four FETs and the bottom four FETs have a common-source and can share the same isolated bias power supply output. Similarly, the two FETs at the switch nodes (SW1, SW2, SW3, N) also have a common source, which enables the FETs to share the same isolated bias power supply output.

The common-drain configuration (which is more common in cases of bidirectional switches) requires two less isolated bias supply power outputs when compared with the common source configuration shown in Section 2. In the common-source architecture, two power switches are placed closely back-to-back. Therefore, the common-source architecture encounters less issues with the differences in Vgs at the gates of the two back-to-back switches due to the parasitic in the PCB layout. However, in the common-drain configuration, give more attention to the differences in Vgs at these gates of switches, especially in the case of SW1, SW2, SW3, and N, since the switch node (with a common source) can have higher parasitic effects (for example, stray inductance) between the two switches.

3.1 Centralized Isolated Bias Power Supply Architecture

In this architecture, a single-stage bias power supply is used with a bias power supply device directly connected to the low-voltage battery. This connection supports a wide input voltage range and works in a closed-loop operation. This type of architecture can be realized using a single device or multiple devices depending on the power rating. A multiwinding transformer is used to give isolated outputs to the different gate drivers. The low-side gate drivers sharing the same ground can be supplied isolated bias power using the same transformer output winding. As shown in Figure 3-2, a 6-winding transformer can be used to supply isolated power in the AC side. If the transformer design is too complicated with 6-windings, using multiple transformers is also possible with two or three windings in the secondary side to reduce the complexity of the transformer design.

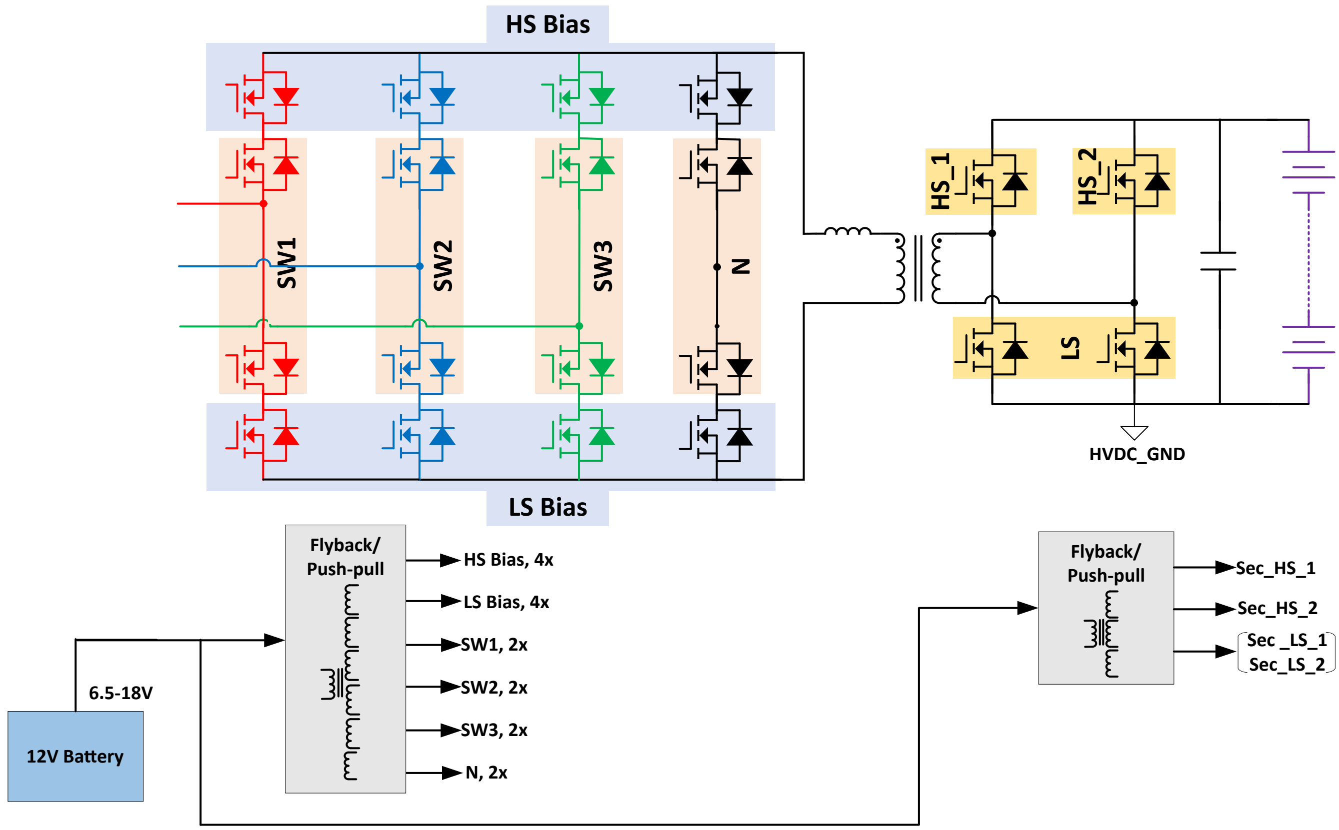

Figure 3-2. Centralized Bias Power Supply Architecture in a Single-Stage OBC With Common-Drain Configuration

The following topologies and associated devices can be used as the preferred choice for the centralized bias power supply architecture:

- Flyback controller: LM5155-Q1, LM5156-Q1, LM515x-Q1, LM3481-Q1
- Flyback converter: LM5180-Q1, LM2518x-Q1
- Push-pull converter: SN6507-Q1

The different topologies for the isolated bias power supply come with certain advantages and trade-offs. A flyback device can help achieve advantages like high efficiency, high load regulation, and high line regulation accuracy for a wide voltage input range. The tightly-coupled flyback transformer design has low leakage inductance, but the trade-off in this design is having a comparatively higher parasitic capacitance across the isolation barrier of the transformer. Appropriate measures in the EMI filter design are sometimes necessary to suppress the EMI and CMTI due to the parasitic capacitance of the transformer. The push-pull device provides good efficiency, high CMTI, lower EMI, and so forth. An extra inductor is needed in the output side to do the duty cycle control for a wide input voltage range operation in push-pull topology.

3.2 Semi-Distributed Isolated Bias Power Supply Architecture

In a semi-distributed architecture, a two-stage isolated bias power supply is used. At the first stage, a wide input voltage range device is used to generate regulated voltage rails. At the second stage, other devices are used to provide isolated bias power to the isolated gate drivers. In this case, not only can a closed loop device be used, but an open loop device can also be used for the isolated bias power supply because the regulated voltage rail is available as an output of first stage. A common occurrence is that the device used during the first stage also generates other required voltage rails for supplying power to the microcontrollers, sensors, and isolators (and so forth) of the onboard charger circuit. Depending on the requirements, an isolated (flyback or push-pull) or non-isolated (SEPIC or buck-boost) topology can be chosen at the first stage.

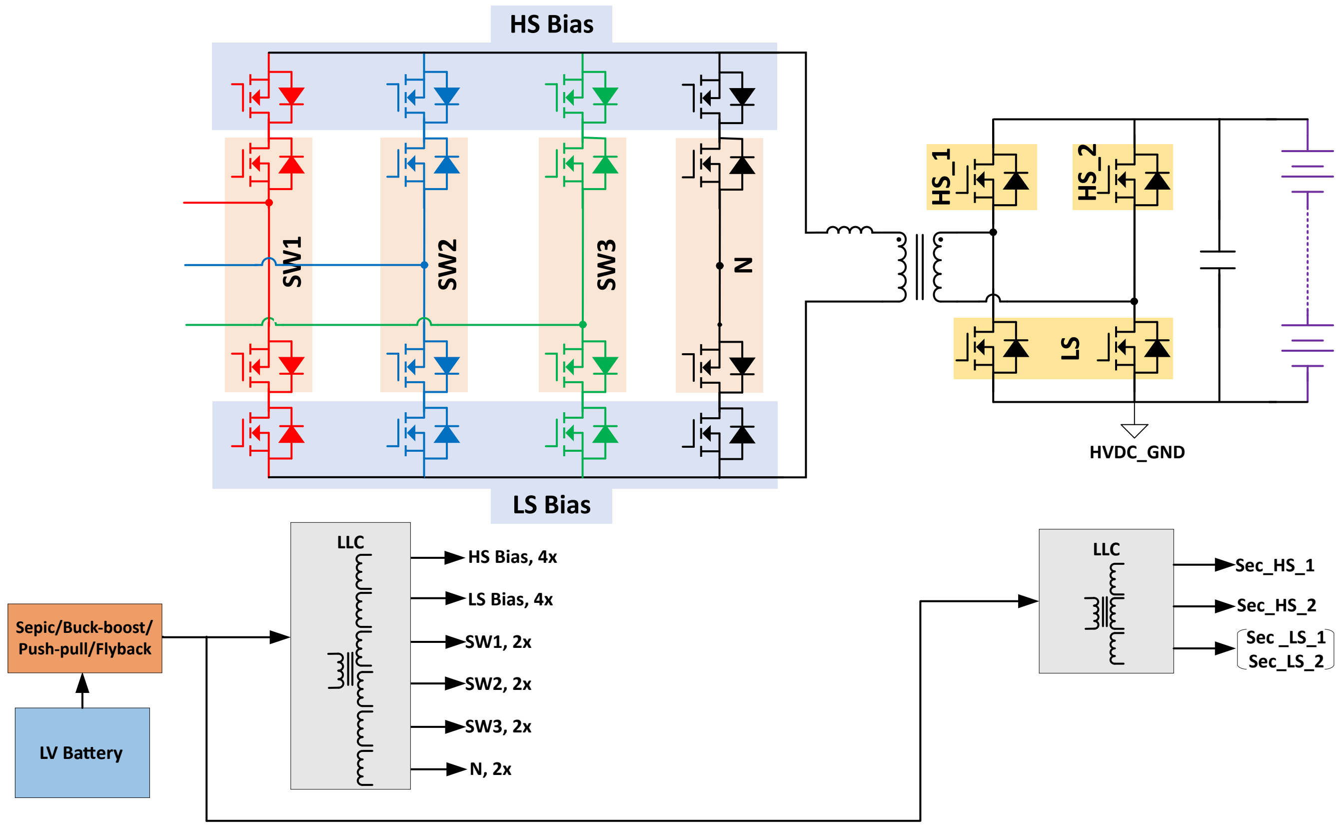

Figure 3-3. Semi-Distributed Bias Power Supply Architecture in Single-Stage OBC With Common-Drain Configuration

For the first stage, flyback and push-pull devices can be used for the choice of isolated topology, in the manner mentioned in the centralized architecture section. For non-isolated topologies, SEPIC and buck-boost converters can be selected. For the second stage, a closed-loop or open-loop isolated bias power device can be chosen. The following topologies and associated devices can be used as the preferred choice for the semi-distributed bias power supply architecture:

- LLC resonant converter: UCC25800-Q1
- Flyback controller: LM5155-Q1, LM5156-Q1, LM515x-Q1, and LM3481-Q1
- Flyback converter: LM5180-Q1 and LM2518x-Q1
- Push-pull converter: SN6507-Q1 and SN6505D-Q1
- SEPIC: LM5155-Q1, LM5156-Q1, LM5157-Q1, and LM5158-Q1
- Buck-boost: TPS55287-Q1, TPS55289-Q1, and LM51xx-Q1

The UCC25800-Q1 is a transformer driver device based on an LLC resonant open-loop operation to generate isolated bias power. The device provides several benefits including good efficiency, low EMI, high CMTI and so forth. Due to the open-loop operation, a regulated voltage rail is preferred for this device. As the leakage inductance in an LLC is a component of the power train, the topology can enable using a higher leakage inductance transformer with an associated reduction in the parasitic primary-secondary capacitance across the isolation barrier of the transformer. These features help improve EMI performance and increase CMTI. An advantage of this increased CMTI is that the LLC resonant topology is now an excellent option for an onboard charger design using GaN switches with high slew rates and for high-frequency operations.

3.3 Bias Power Supply Using a DC-DC Converter Module

The use of a DC-DC converter module with an integrated transformer is a potentially beneficial choice in a distributed architecture where the smaller size and higher power density is the major focus of the design. These modules are switching at a very high frequency range of 11MHz to 15MHz, which allows for a reduction in the size, height, and weight of a built-in transformer, hence, decreasing the space required by the PCB. These integrated DC-DC converters provide a high level of integration, an elimination of many external components, and help designers achieve robust designs against vibrations with easier PCB layouts. The integrated modules operate in close-loop control, providing a tightly-regulated output, which is advantageous in cases of bidirectional GaN switches with narrow Vgs ranges.

TI offers several variants of the integrated DC-DC modules. These variants provide flexibility for selecting the device that is appropriate for the available input voltage rail of the system and the required output voltage of the system. Table 3-1 shows all variants and the technical specifications.

Table 3-1. Texas Instruments Integrated Transformer DC-DC Converter Modules

Part Number	Isolation Strength	V_{IN} | V_{OUT} Nominal	VIN Range	VOUT Range	Typical Power
UCC14240-Q1 UCC14241-Q1	Basic (3kV$_{RMS}$) Reinforced (5kV$_{RMS}$)	24V$_{IN}$ | 25V$_{OUT}$	21V–27V	15V–25V	2.0W
UCC14140-Q1 UCC14141-Q1	Basic (3kV$_{RMS}$) Reinforced (5kV$_{RMS}$)	12V$_{IN}$ | 25VOUT	10.8V–13.2V 8V–18V	15V–25V 15V–25V	1.5W 1.0W
UCC14340-Q1 UCC14341-Q1	Basic (3kV$_{RMS}$) Reinforced (5kV$_{RMS}$)	15V$_{IN}$ | 25V$_{OUT}$	13.5V–16.5V	15V–25V	1.5W
UCC14130-Q1 UCC14131-Q1	Basic (3kV$_{RMS}$) Reinforced (5kV$_{RMS}$)	12–15V$_{IN}$ | 12V–15V$_{OUT}$	12V–15V 10V–18V 15V–18V 14V–18V	12V–15V 10V–12V 15V–18V 10V–18V	1.5W, 1.0W, 1.5W 1.0W
UCC15240-Q1 UCC15241-Q1	Basic (3kV$_{RMS}$) Reinforced (5kV$_{RMS}$)	24V$_{IN}$ | 25V$_{OUT}$	21V–27V	15V–25V	2.5W
UCC34141-Q1	Reinforced (5kV$_{RMS}$)	12V$_{IN}$ | 25V$_{OUT}$	8V–20V 5.5V–8V	V_{DD-COM} 15V–20V V_{EE-COM} −2V–(−)8V	1.5W >0.3W
UCC35131-Q1	Reinforced (5kV$_{RMS}$)	12V$_{IN}$ | 12V–20V$_{OUT}$	10.8V–13.2V 8V–20V 5.5V–8V	V_{DD-COM} 15V–20V V_{EE-COM} −2V–(−)8V	2.0W 1.5W >0.3W

The requirement of the preregulator to provide a regulated voltage rail to integrated DC-DC modules depends on the power requirement of the isolated gate drivers. As mentioned in Table 3-1, power derates in case of a wide input voltage range while connecting the integrated DC-DC module directly with the battery.

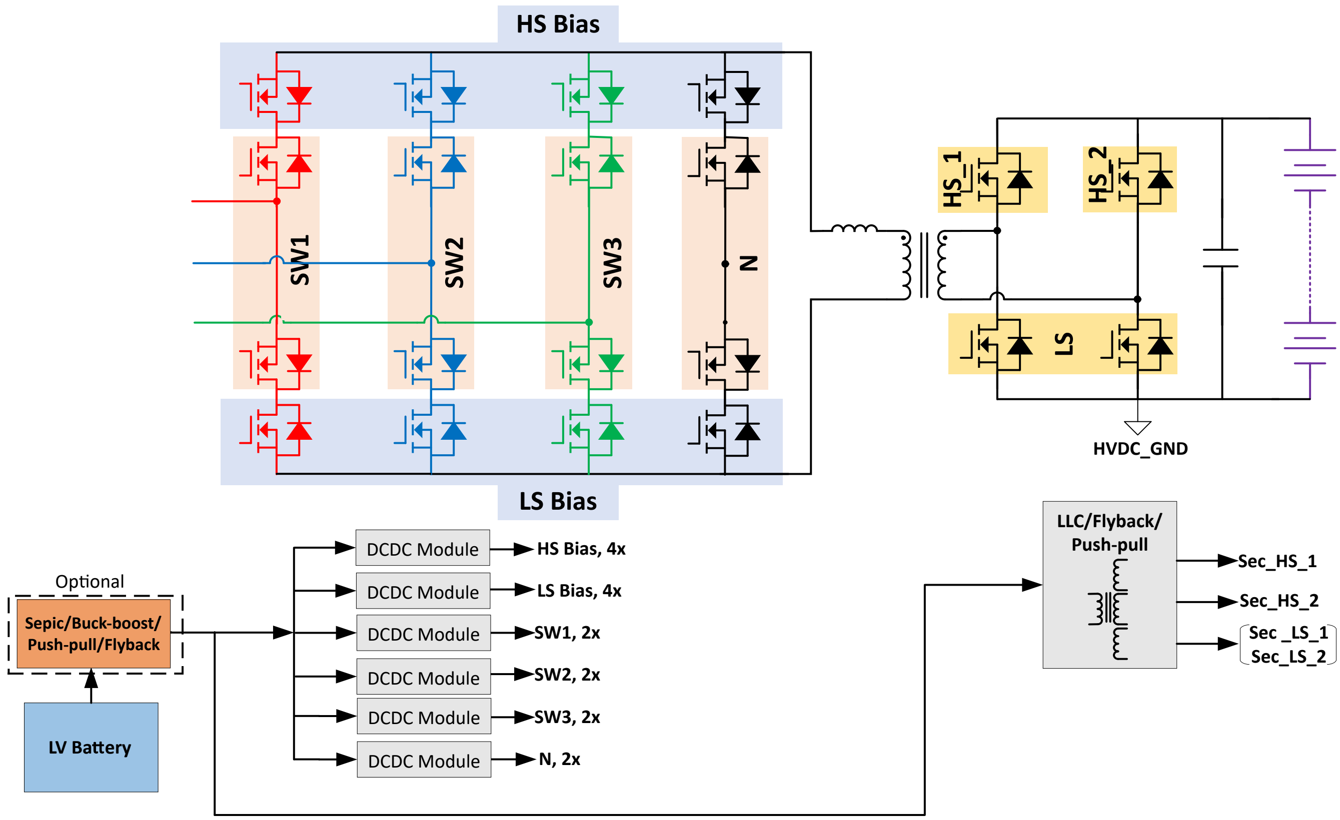

Figure 3-4. Bias Power Supply Architecture in Single-Stage OBC With Common-Drain Configuration Using the DC-DC Module

4 Isolated Bias Power Supply Using Gate Driver to Drive the Transformer

For isolated bias power supply generation, a gate driver can drive the transformer (typically, a low-side gate driver like UCC27624-Q1). In this approach, an additional device, like a clock, microcontroller, or so forth, generates PWM signals of a certain duty cycle, which then drives the transformer to generate isolated bias power. However, the architectures mentioned earlier in this paper are specifically targeted for isolated bias power supply applications, and these architectures are preferred compared to the approach using a gate driver to drive a transformer for isolated bias power supply generation.

The following devices can be used as the preferred choice for a PWM generator and non-isolated gate driver to drive a transformer to generate isolated bias power for an isolated gate driver:

- PWM controller: UC2843A-Q1, UCC28C56H-Q1, TPS40210-Q1, and LM25037-Q1
- Gate driver: UCC27624-Q1 and UCC27524A-Q1

5 Redundancy in the Isolated Bias Power Supply Architecture

Functional safety is an important topic in the automotive industry. A redundant architecture offers better reliability from a functional safety point-of-view, but the design potentially incurs additional costs in the system. However, redundancy in the isolated bias power supply can make the whole system more reliable. This redundancy means that isolated bias supplies are getting power from both high-voltage and low-voltage batteries. The redundancy can be provided to either all devices or only to the low-side or high-side devices. In the redundant architecture, in case of a failure from either low-voltage or high-voltage batteries, all the gate drivers remain powered from the other battery. In general, the gate drivers are primarily powered using the low-voltage battery. Whereas, the high-voltage battery is used to provide redundancy.

The devices mentioned in the *High-Voltage Isolated Bias Power Supply* section are an excellent choice for providing redundancy from a high-voltage battery.

6 Summary

With the current market trend shifting from dual-stage on board chargers to single-stage on board chargers, the architecture of the isolated bias power supply is also evolving with this trend, especially in cases of bidirectional switches with common drain. This paper summarized several possible architectures for isolated bias power supplies for single-stage OBCs, including some of the most commonly used architectures. Based on the chosen architecture, this paper examined the next steps of selecting a topology (flyback, push-pull, LLC resonant, integrated DC-DC module, and so forth) and the associated devices. Design complexity and costs and functional safety requirements play vital roles in the decision process for the type of architecture and topology to use.

7 Terminology

AC	Alternating current
CAN	Controller area network
DC	Direct current
EV	Electric vehicle
FET	Field-effect transistor
HEV	Hybrid electric vehicle
HS	High side
LDO	Low-dropout regulator
LLC	Inductor-inductor capacitor
LS	Low side
OBC	On board charger
OEM	Original equipment manufacturer
PFC	Power factor correction
PMIC	Power management integrated circuits
Pri	Primary
PSR	Primary side regulated
Sec	Secondary
SEPIC	Single ended primary inductor converter
SOC	State of charge
V_{GS}	Gate-to-source voltage
V_{IN}	Input voltage
V_{OUT}	Output voltage