Technical White Paper

Isolated Bias Power Supply Architecture for HEV and EV Onboard Chargers

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ABSTRACT

The numbers of electric vehicles (EV) and hybrid electric vehicles (HEV) in the automotive industry are increasing. An onboard charger is one of the significant parts in the overall electronics of the HEVs and EVs, which is used to charge the high voltage battery. In the onboard charger circuit design, isolated bias power supply contains a major part of the circuit. These chargers are used to supply the required power to the gate drivers. There are several possible architectures for the isolated bias power supply to the gate drivers in the power factor correction (PFC) and DC-DC converter stages of the onboard charger. These architectures also influence the choice of the topologies and related devices used for the isolated bias power supply in the onboard charger.

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1 Introduction

Isolated bias supply provides power to the different gate-driver circuits in HEVs and EVs. There are different topologies to design an isolated bias power supply. 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 trade-offs 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) need different input voltage range for gate-source voltage. Therefore, isolated bias power supply architecture and selection of devices also depend on the switches used in the design.

Isolated bias power supplies take power either from the low-voltage battery or from the high-voltage battery of the HEV or EV. Based on the power source, the isolated bias power supplies can be divided in 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 the pre-regulators. The pre-regulators are needed depending on the wide input voltage range capability of the device. Although low-voltage batteries are common as a power source for isolated bias power supplies, sometimes both low-voltage and high-voltage batteries are used to provide redundancy in the system. A redundant power supply can lead to achieve higher functional safety of an overall system.

Figure 1-1 shows a generic onboard charger circuit with PFC, DC-DC primary, and DC-DC secondary stages. The switches are named as PFC_HS_1, Pri_HS_1, Sec_HS_1, and so forth. The first part of this nomenclature indicates that whether the switch belongs to PFC or DC-DC primary or DC-DC secondary stage of the onboard charger. The second part shows whether the circuit uses a high-side or low-side switch. The third part shows the switch number of the high or low side. In the same fashion, consider the same nomenclature for the gate driver of each of these switches and the isolated bias power supply to the gate drivers. In the figures in this document, this nomenclature is used to describe the different isolated bias power supply architecture.

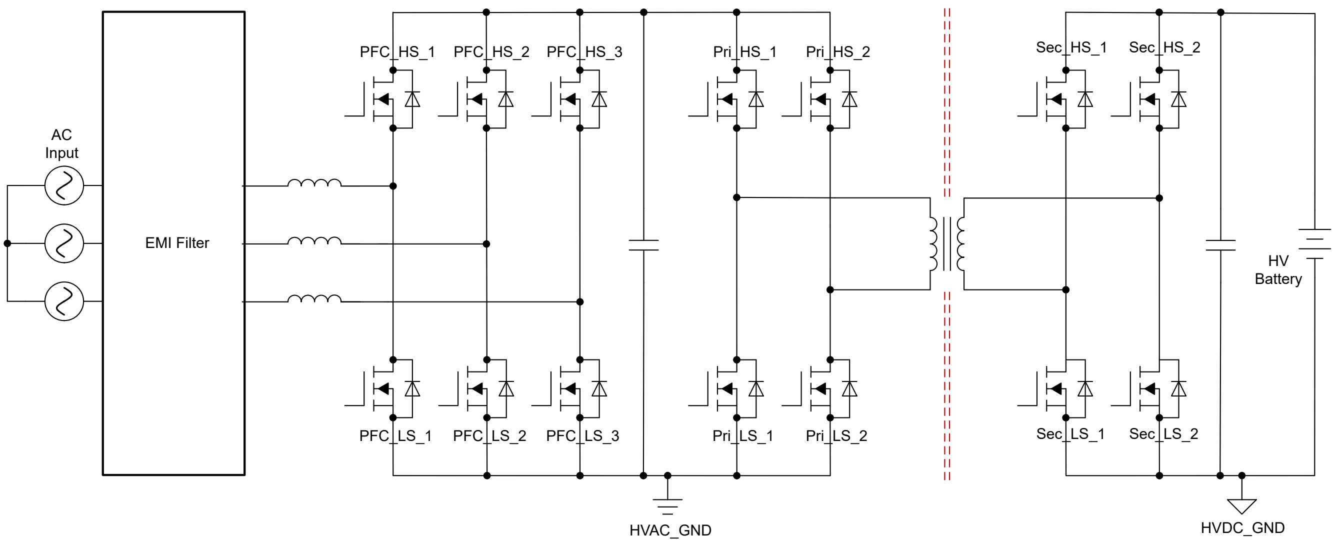

Figure 1-1. Onboard Charger Generic Circuit

1.1 Low-Voltage Isolated Bias Power Supply

Low-voltage isolated 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 can be still relevant for 48V low-voltage battery designs. In that case, one option is to have a converter to lower the voltage to use the same devices or another option is to have 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 (as an example: 8V–16V). In case of cold crank and load dump scenarios, the input voltage range requirement goes further down and up, respectively. There can be differences in this 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 pre-regulator is needed between low-voltage battery and 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 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 UCC1434x-Q1 UCC1524x-Q1

(1) Depends on the variant of the device.

1.2 High-Voltage Isolated Bias Power Supply

High-voltage isolated 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 the most common in HEVs and EVs. The isolated bias supply connected to the high-voltage battery needs to support a wider input voltage range. The need for wide input voltage range support is similar to the low-voltage battery: SOC and load dump scenarios of the high-voltage battery. Based on the SOC of the battery, a wider input voltage range needs to be supported. For example, commonly considered voltage ranges are 240V–450V for a 400V battery and 550V–950V 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 isolated bias power supply, mostly the battery is used to provide redundancy. Flyback topology is usually selected for such a high and wide input voltage range from a technical perspective as well with respect to minimizing costs.

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

Device	UCC28C5x-Q1	UCC28700-Q1	UCC28730-Q1	UCC28740-Q1	UCC28781-Q1
Switching Type	Hard-switched	Valley switching	Valley switching	Valley switching	Zero-voltage switching (ZVS)
Feedback Regulation(1)	Primary, Secondary (Optocoupler)	Primary	Primary	Secondary (Optocoupler)	Secondary (Optocoupler)
Typical Power Levels	20W–100W	2W–50W	2W–50W	2W–50W	50W–150W

(1) Primary side regulation removes the optocoupler from the design.

2 Centralized Isolated Bias Power Supply Architecture

In this architecture, a single-stage bias power supply architecture is used in which a bias power supply device is directly connected to the low-voltage battery. This connection supports a wide input voltage range and works in closed-loop operation. This kind of architecture can be realized using a single or multiple device depending on the power rating. A multi-winding transformer is used to give isolated output to the different gate drivers. The low-side gate drivers share the same ground can be supplied isolated bias power using the same transformer output winding.

Figure 2-1 shows how three isolated devices with multi-winding transformers are used for PFC, DC-DC primary, and DC-DC secondary stage isolated bias supply. For each stage, low-side gate drivers share the power supply from same output winding of the transformer; whereas, each high-side gate driver has a separate output winding of the transformer.

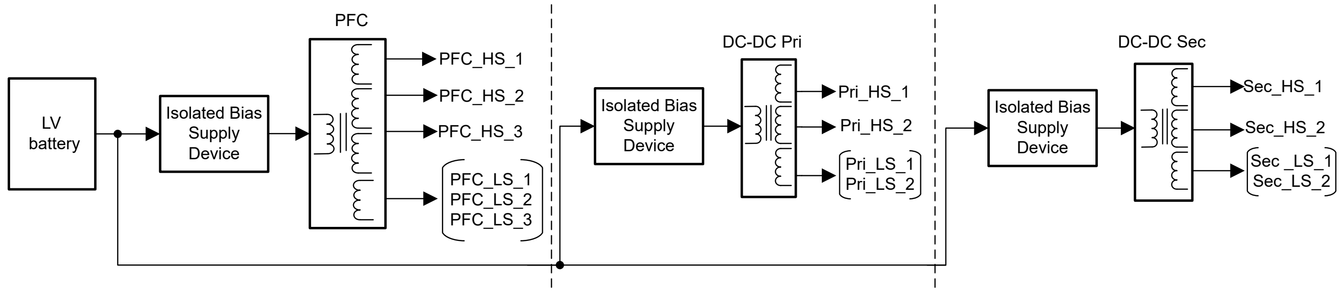

Figure 2-1. Centralized Architecture With Three Isolated Bias Power Devices

Figure 2-2 shows the use of two isolated devices with multi-winding transformers. From the first isolated bias power device, all five low-side gate drivers of the *PFC and DC-DC Pri* stage shares the power supply from the same output winding of the transformer since all of these are sharing the same ground. Each high-side gate driver has a separate output winding of the transformer. From the second isolated bias power supply device, the operation is similar to the previous case. There are *six* output windings in the transformer used for the *PFC and DC-DC Pri stage*. A higher number of transformer windings results in complex transformer design and increases the challenges in output regulation. Additionally, the load on one output winding, which is used to supply power to all five gate drivers of the low side is higher compared to other five windings used for each of the high-side switches separately.

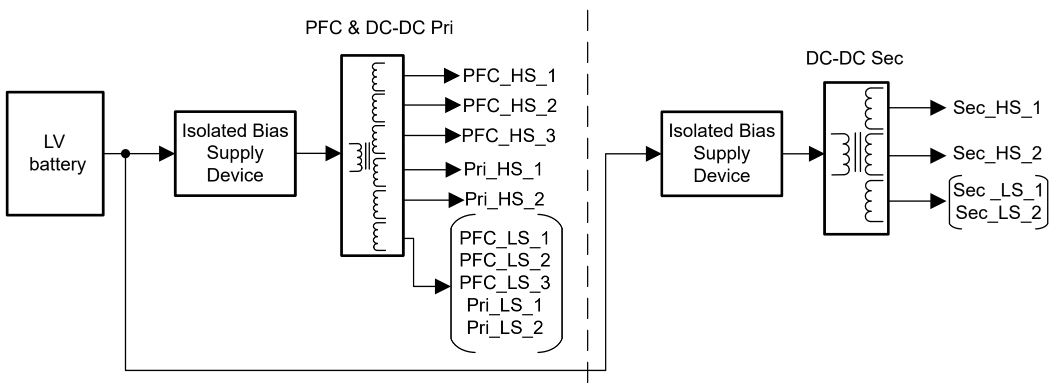

Figure 2-2. Centralized Architecture Using Two Isolated Bias Power Devices

Figure 2-3 uses a single isolated device with multi-winding transformers. Nine output windings of the transformer is needed to supply the power from a single isolated bias device. Seven output windings of the transformer is used for seven high-side gate drivers, one winding for five low-side gate drivers of *PFC and DC-DC Pri stage* and one winding for two low-side gate drivers of the *DC-DC Sec* stage is used. The high number of transformer output winding results in a complex transformer design and increased challenges in output regulation. Also, the load on output windings of the transformer is not same; therefore, this factor must be accounted for during the transformer design. The PCB layout for routing the traces is complicated in this kind of bias power supply architecture since long traces need to be drawn from the transformer output to the gate drivers of the *PFC and DC-DC stages*. A controller device with external FET can be a better choice compared to a converter with an internal FET in the situation of delivering sufficient power required for gate drivers of the onboard charger.

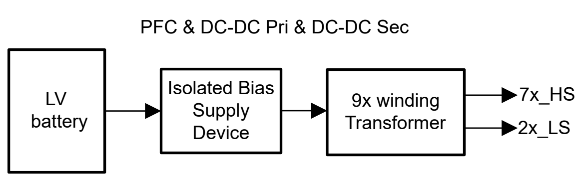

Figure 2-3. Centralized Architecture Using Single Isolated Bias Power Devices

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

- Flyback controller: LM5155x-Q1, LM5156x-Q1, LM34xx-Q1
- Flyback converter: LM518x-Q1, LM2518x-Q1
- Push-pull converter: SN6507-Q1

Different topologies for the isolated bias power supply come with certain advantages and trade-offs. A flyback device can help to 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 this design comes with the trade-off of having comparatively higher parasitic capacitance across the isolation barrier of the transformer. Appropriate measures in the EMI filter design are sometimes needed 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 wide input voltage range operation.

3 Semi-distributed Isolated Bias Power Supply Architecture

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

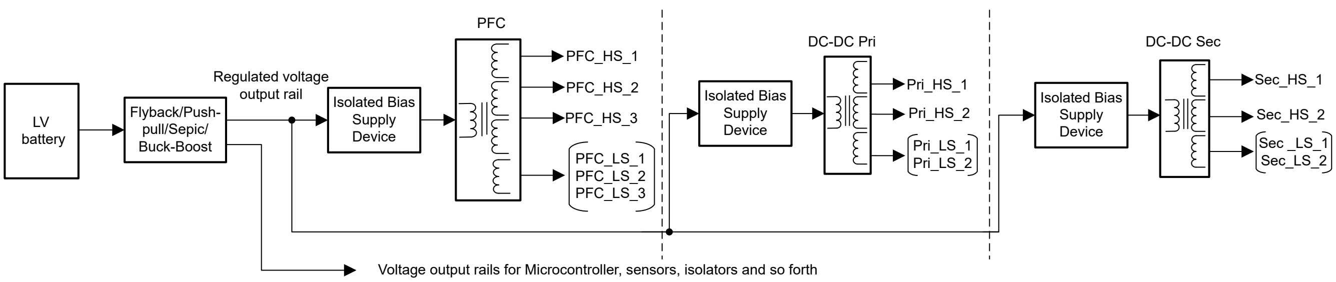

Figure 3-1. Semi-distributed Isolated Bias Power Supply Architecture

For the first stage, flyback and push-pull devices can be used as mentioned in the centralized architecture section for the choice of isolated topology. 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: LM5155x-Q1, LM5156x-Q1, LM34xx-Q1
- Flyback converter: LM518x-Q1, LM2518x-Q1
- Push-pull converter: SN6507-Q1, SN6505-Q1
- SEPIC: LM5155x-Q1, LM5156x-Q1, LM5157x-Q1, LM5158x-Q1
- Buck-boost : TPS55287x-Q1, LM51xx-Q1

The UCC25800-Q1 is a transformer driver device based on 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 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 a higher leakage inductance transformer to be used with an associated reduction in the parasitic primary-secondary capacitance across the isolation barrier of the transformer. These features help to better EMI performance and higher CMTI. Using the advantage of high CMTI capability, the LLC resonant topology can be an excellent choice for an onboard charger design using GaN switches with high slew rate and high-frequency operation.

4 Distributed Architecture Using DC-DC Converter Module

Use of an integrated DC-DC transformer module can be the preferable choice for a distributed type of architecture. These integrated modules have an integrated transformer, which is switching at a very high frequency range of 11MHz to 15MHz. Using an integrated transformer module eliminates the need of external transformers, which results in a reduction in size and height of the overall system. An integrated transformer provides higher robustness to vibration. Additionally, these integrated DC-DC modules need only a few external discrete components; therefore, this architecture is simpler from the design and layout perspective.

TI offers several variants of the integrated DC-DC modules. These variants give the flexibility to choose the appropriate device, based on the availability of the input voltage rail in the system and required output voltage. Table 4-1 shows all variants and the technical specifications.

Table 4-1. Texas Instruments Integrated Transformer Designs

Part Number	Isolation Strength	V_{IN} | V_{OUT} Nominal	V_{IN} Range	V_{OUT} 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$_{IN}$ | 25V$_{OUT}$	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$_{IN}$ | 12–15V$_{OUT}$	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

In a fully distributed architecture of the onboard charger, the architecture can be designed in different ways. The requirement of the pre-regulator to provide a regulated voltage rail to the integrated DC-DC modules depends on the power requirement for the gate drivers. As mentioned in Table 4-1, there is power derating in case of a wide input voltage range while connecting the integrated DC-DC module directly with the battery.

As Figure 4-1 shows, a separate integrated DC-DC module is used for each high-side gate driver and low-side gate drivers are supplied using flyback or push-pull devices using a multi-winding transformer. For the low side, it is possible to use same output winding of the transformer to supply bias power to multiple gate drivers that share the same ground.

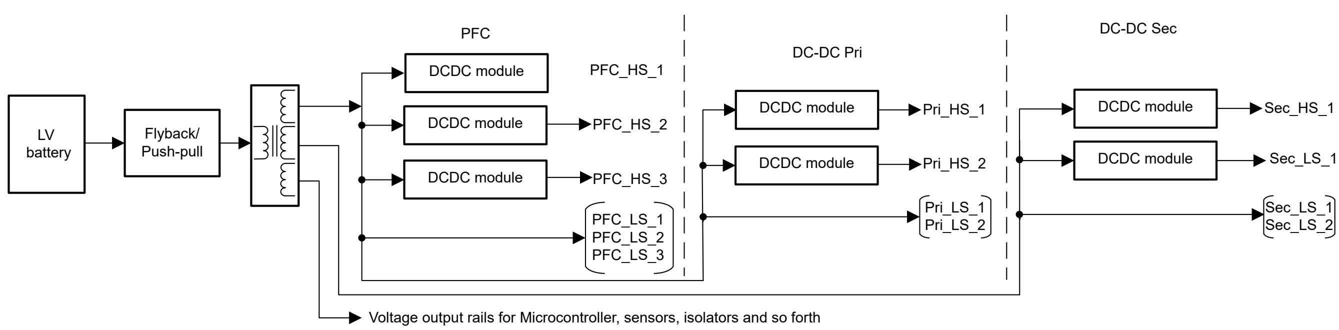

Figure 4-1. Architecture Using Combination of Flyback and Push-Pull and a DC-DC Module

Isolated bias power supply for the high side can be done using the bootstrap approach. As Figure 4-2 shows, isolated bias power for high-side gate drivers is generated using the bootstrap circuit. In the case of using a DC-DC module, each DC-DC module can be used to supply the low side directly and the high side using bootstrap. Other topologies like flyback, push-pull, and so forth, can be also be realized using the bootstrap approach. For a design with high switching frequency, especially in case of use of GaN switches, the power loss in the bootstrap diode can lead to thermal challenges. Therefore, the bootstrap approach can be more desireable in the case of low switching frequency designs.

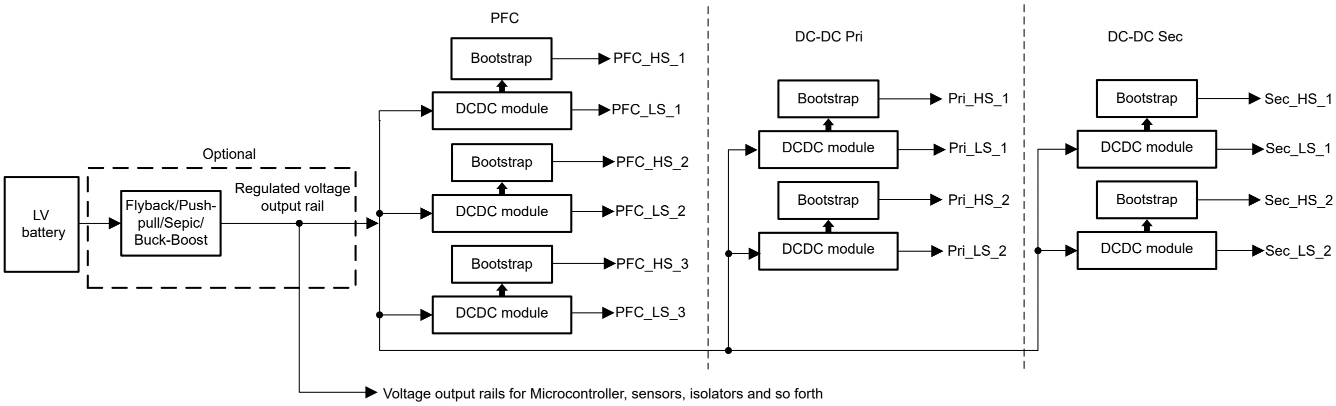

Figure 4-2. Isolated Bias Power Supply Architecture Using Bootstrap Approach

Figure 4-3 shows a fully distributed architecture that can also be used for the isolated bias power supply to the gate drivers. Although this approach can be considered good from the safety point of view, simple design efforts, and so forth — due to the high number of devices, the cost is high for such architecture.

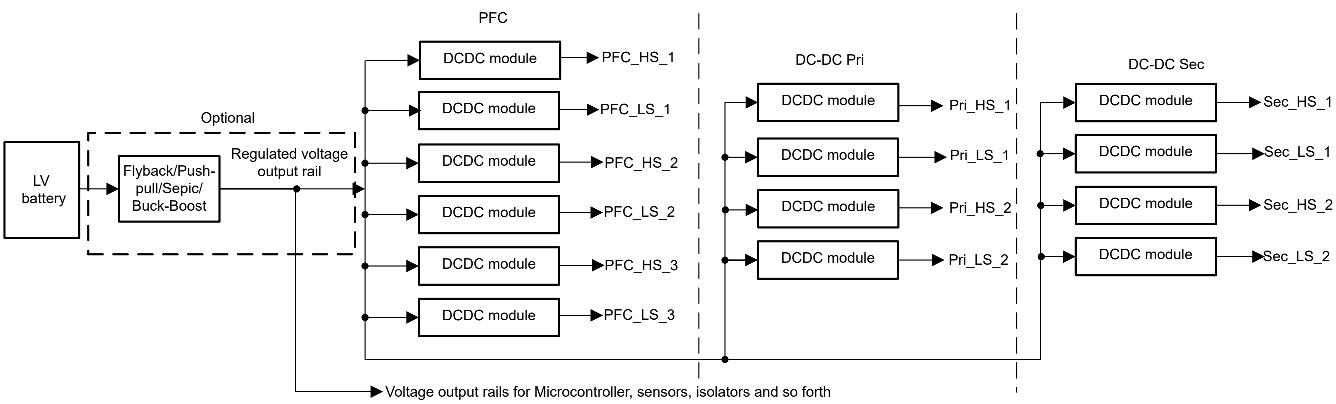

Figure 4-3. Isolated Bias Power Supply Using Fully Distributed Architecture

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

Figure 5-1 shows how gate drivers can be used to drive the transformer to generate the isolated bias power supply. In this approach, PWM signals of certain duty cycle are fed to the gate driver, which drives the transformer to generate isolated bias power supply. A clock, microcontroller, or a particular IC (and so forth) can be used as the PWM generator. However, currently several devices mentioned in the earlier architectures in this paper are available and are specifically targeted for isolated bias power supply applications. These architectures are preferred compared to the approach of using a gate driver to drive a transformer for isolated bias power supply generation.

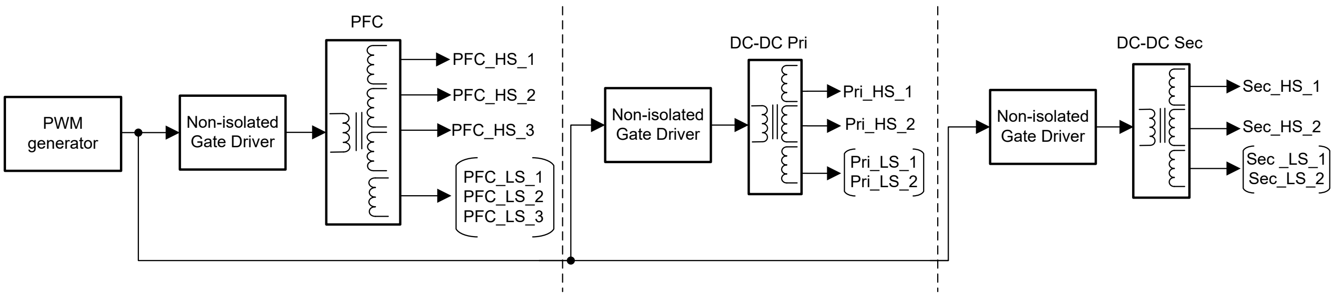

Figure 5-1. Architecture Using Gate Driver to Drive the Transformer for Isolated Bias Power Supply Generation

6 Redundancy in the Isolated Bias Power Supply Architecture

Functional safety is an important topic in the automotive industry. To make the whole system more reliable, redundancy in the isolated bias power supply can be provided. This means that isolated bias supplies are getting power from both high-voltage and low-voltage batteries. Redundancy can be provided either to all devices or only to the low-side or high-side devices. In the redundant architecture, in case of a failure either from low-voltage or high-voltage batteries, all the gate drivers are still 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. A redundant architecture has better reliability from the functional safety point of view but the design adds additional cost in the system. The devices mentioned in the *High-Voltage Isolated Bias Power Supply* section are an excellent choice to provide redundancy from a high-voltage battery.

7 Summary

The isolated bias supply is an important part of an onboard charger circuit. There are several isolated bias power supply architectures for onboard chargers and some commonly-used architectures, are shown in this paper. Based on the chosen architecture, the next step is to choose a topology (flyback, push-pull, LLC resonant, integrated DC/DC module, and so forth) and the associated devices. Design complexity, functional safety requirements, and cost play the main role in the decision of which type of architecture and topology to use.

8 Terminology

AC	Alternating current
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
OEM	Original equipment manufacturer
PFC	Power Factor Correction
Pri	Primary
PSR	Primary side regulated
Sec	Secondary
SEPIC	Single ended primary inductor converter
SOC	State of charge
V_{IN}	Input voltage
V_{OUT}	Output voltage

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