Technical White Paper

Bias Power Supply Architecture for HEV/EV HVLV DCDC Converters

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ABSTRACT

Number of Electric vehicles (EV) and hybrid electric vehicles (HEV) are constantly growing in automotive sector. A HVLV DCDC converter is one of the significant parts in the overall electronics of the HEVs and EVs, which is primarily used to charge the low voltage battery from the high voltage battery. In the HVLV DCDC circuit design, bias power supply contains a major part. These are used to supply the required power to the gate drivers, microcontrollers and sensors and so forth. There are different possible architectures for the isolated and non-isolated bias power supply of the HVLV DCDC converter. These architectures also influence the choice of the topologies and associated devices in the circuit design.

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Trademarks

1 Introduction

The bias power supply for HVLV DCDC converter can be mainly divided in to two parts: Isolated bias power supply and non-isolated bias power supply. Considering that the microcontroller is located in the LV secondary side of the converter, isolated gate drivers are required at the HV primary side. Therefore, isolated bias power supply are required to provide power to the isolated gate drivers. 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.

Considering the microcontroller is located at low voltage side and sharing same ground as low voltage battery, all devices like non-isolated gate drivers, active clamp circuit gate drivers, sensors, controller area network (CAN) and so forth of the secondary side of DCDC converter can be powered using non-isolated bias supply. From a low voltage battery, non-isolated DCDC converters like buck converter, Single-Ended Primary Inductor Converter (SEPIC) or a buck-boost converter can be used to generate a regulated voltage rail. This regulated voltage rail can be further used to distribute required bias power to the primary and secondary side devices.

Bias power devices 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 bias power supplies can be divided in two groups: low-voltage bias power supplies and high-voltage bias power supplies. The 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 HVLV DCDC converter circuit with DC-DC primary, and DC-DC secondary stages. The switches are named as Pri_HS_1, Pri_HS_2, and so forth. The first part of this nomenclature indicates that whether the switch belongs to DC-DC primary or DC-DC secondary stage of the converter. 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.

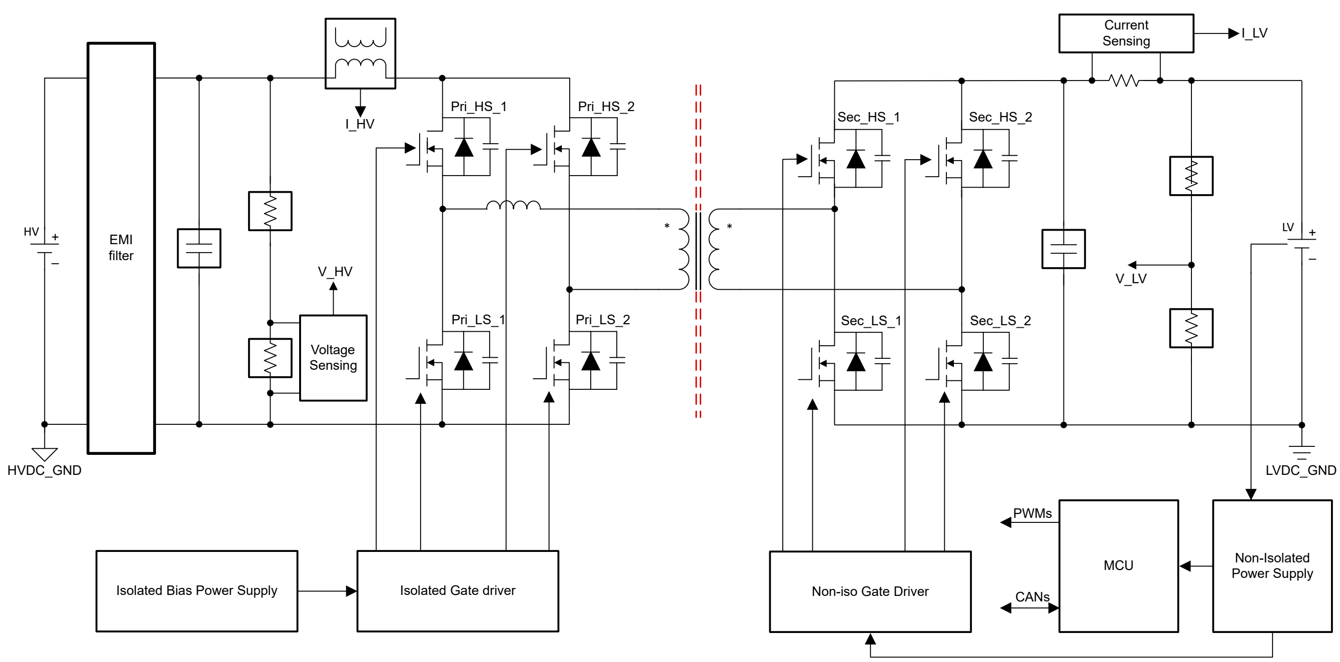

Figure 1-1. HVLV DCDC Generic Circuit

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 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
Advantages	High efficiency Low EMI High CMTI	Wide Vin range High line regulation	High efficiency Wide Vin range Highload and line regulation	No external transformer Robustness to vibration Small size and low height
Challenges	Requirement of Pre-regulator	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 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 isolated bias power supply architecture is used in which an isolated 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 isolated gate drivers in the primary side. The low-side gate drivers share the same ground can be supplied power using the same transformer output winding.

Figure 2-1 shows how one isolated device with multi-winding transformers are used for DC-DC primary stage isolated bias supply. Low-side isolated gate drivers share the power supply from same output winding of the transformer; whereas, each high-side isolated gate driver has a separate output winding of the transformer. A sepic converter is used to get a regulated 12V or 15V or so forth voltage rail used for non-isolated gate drivers and other subsystems like active clamp circuit and so forth at the secondary side. A wide Vin buck converter directly connected with LV battery is used to generate 5V non-isolated power supply. Rather than connecting with LV battery directly, it is also possible to use the output of sepic converter as input for this buck converter. The 5V output voltage rail is used as input to the dual buck converter to generate 3.3V and 1.2V voltage rails to supply power to the microcontroller. This is based on the assumption that microcontroller is located at LV battery side and sharing same ground with LV battery. This 5V rail can be used for other devices at secondary side like CAN, sensors and isolators, and so forth.

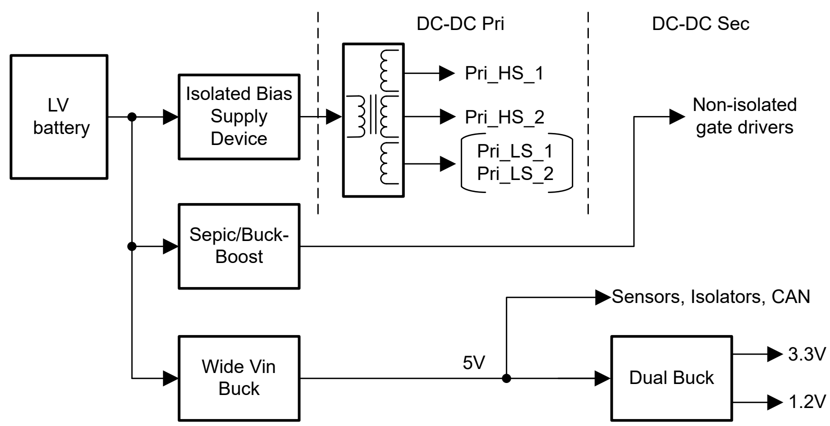

Figure 2-1. Centralized Architecture using Discrete Non-isolated Devices

Figure 2-2 shows the use of PMIC in the power supply. Rather than using the discrete approach of wide Vin buck and dual buck, a functional safety compliant PMIC can be used to supply the power to the microcontroller. Texas Instruments offers the following functional safety compliant PMIC devices, which can be a preferred choice to use in the bias power supply architecture mentioned in Figure 2-2:

- PMIC: TPS65386x-Q1 (ASIL-D), TPS65036x-Q1 (ASIL-B)

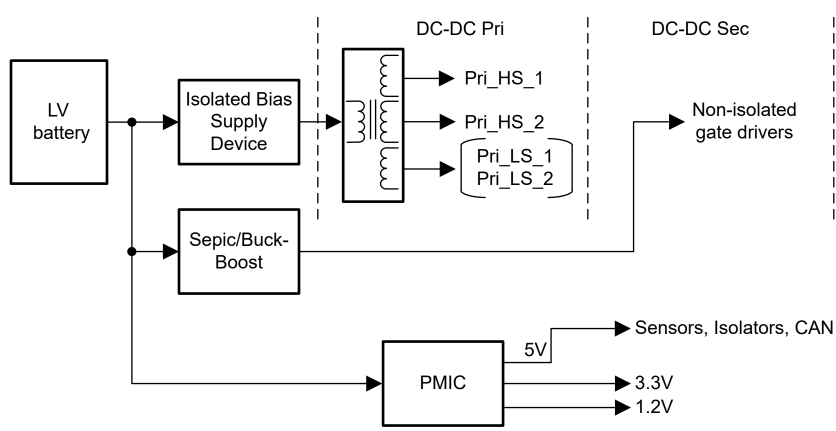

Figure 2-2. Centralized Architecture Using PMIC

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
- SEPIC: LM5155x-Q1, LM5156x-Q1, LM5157x-Q1, LM5158x-Q1
- Buck-boost : TPS55287x-Q1, LM51xx-Q1
- Wide Vin buck: LMR60440-Q1, LM61440-Q1
- Dual buck: TPS62441-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 common mode current 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 for the push-pull device 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 isolated 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 isolated gate drivers. In this case, not only a closed loop device but an open loop device can also be used for isolated bias power supply 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.

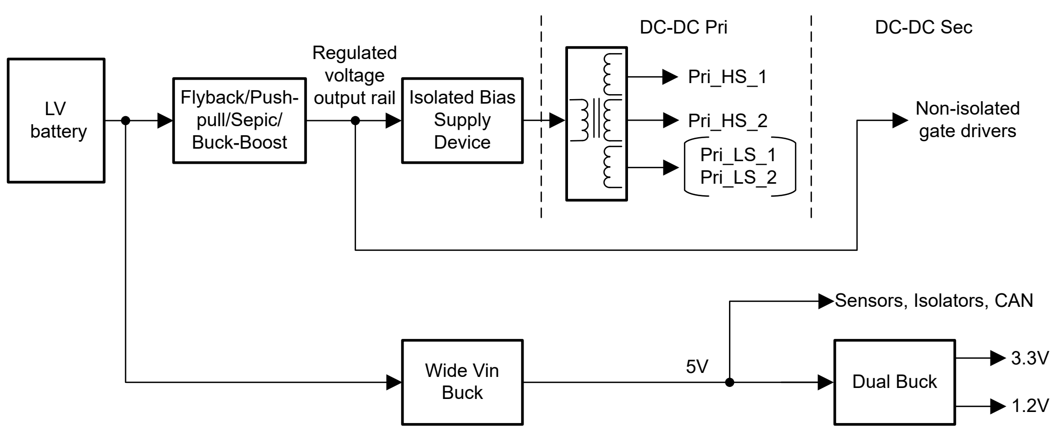

Figure 3-1. Semi-Distributed Isolated Bias Power Supply Architecture

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, TPS55289-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 Bias Power Supply 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

The requirement of the pre-regulator to provide a regulated voltage rail to the integrated DC-DC modules depends on the power requirement of the isolated 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. Whereas, the low-side gate drivers are supplied using a single integrated DC-DC module. For the low side, it is possible to use same integrated DC-DC module to supply bias power to multiple gate drivers that share the same ground. Depending on the total required power needed for two low side isolated gate drivers, those are powered using a single integrated DC-DC module device, a higher power rated variant can be preferred.

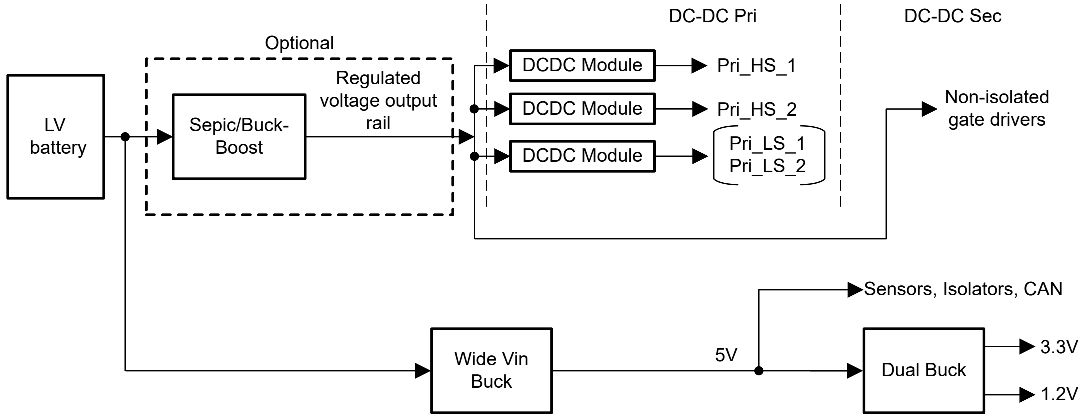

Figure 4-1. Bias Power Supply Architecture Using DC-DC Modules

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 desirable in the case of low switching frequency designs only.

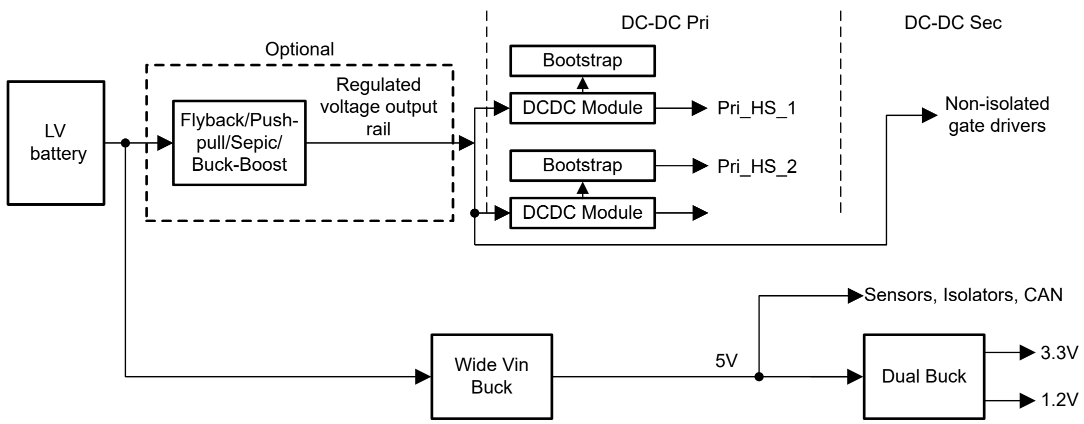

Figure 4-2. Bias Power Supply Architecture Using Bootstrap Approach

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.

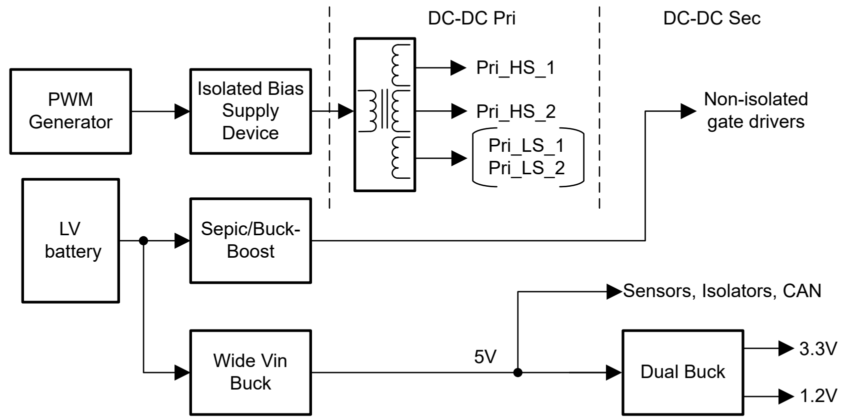

Figure 5-1. Architecture Using Gate Driver to Drive the Transformer for Isolated Bias Power Generation

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

- PWM controller: UCC2843A-Q1, UCC28C56H-Q1, TPS40210-Q1, LM25037-Q1
- Gate Driver: UCC27624-Q1, UCC27282-Q1

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. Figure 6-1 shows the bias power supply architecture including redundant power supply form high voltage battery.

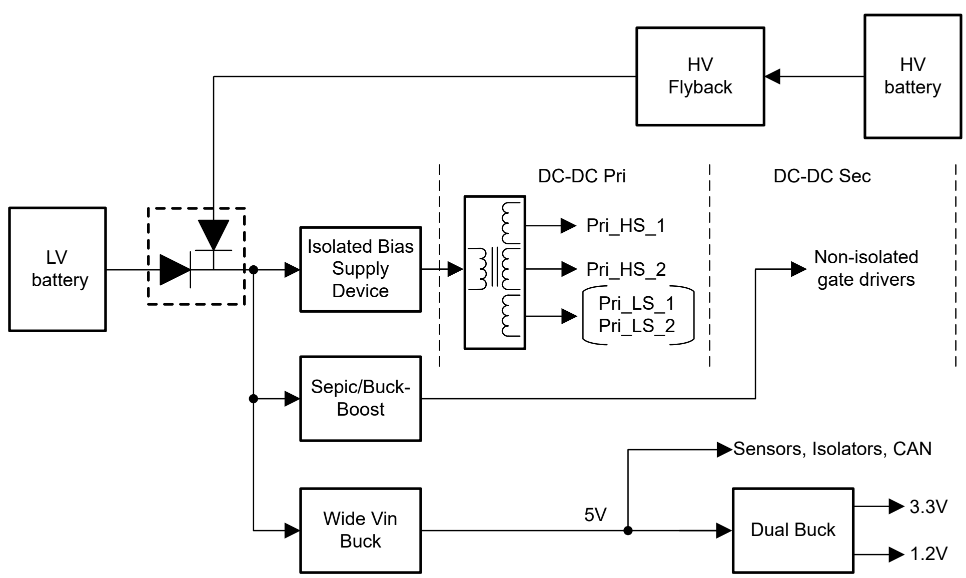

Figure 6-1. Centralized Architecture Using Single Isolated Bias Power Devices

Redundancy can be provided either to all devices or only to the low-side or high-side devices depending on the safety requirements. 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 High-Voltage Isolated Bias Power Supply are an excellent choice to provide redundancy from a high-voltage battery.

7 Summary

The bias power supply is an important part of a HVLV DCDC converter design. There are several possible bias power supply architectures for HVLV DCDC converter 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, size, functional safety requirements, and cost play the main role in the decision of which type of architecture, topology and device to use.

8 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
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_{IN}	Input voltage
V_{OUT}	Output voltage