Technical White Paper

Isolated Bias Power Supply Architecture for HEV and EV Traction Inverters

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ABSTRACT

The automotive industry is transitioning from combustion engines to electric vehicles (EV) and hybrid electric vehicles (HEV). One of the key parts of an EV and HEV system is a *Traction Inverter*. The traction inverter takes the DC input power from the high-voltage (HV) battery and provides the controlled AC power to the e-motor. Along with power Switches and gate drivers, isolated bias power supply is a major portion in the traction inverter circuit. One of the main functions of the isolated bias supply is to provide the required power to the gate drivers. There are several possible architectures for the isolated bias power supply. These architectures also influence the choice of the topologies and associated devices.

Table of Contents

List of Figures

List of Tables

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.

Isolated bias power supplies take power either from the low-voltage (LV) battery or from the high-voltage battery of the HEV, 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, LV batteries are common as a power source for isolated bias power supplies, often both LV and HV batteries are used to provide redundancy in the system. A redundant power supply can lead to achieve higher functional safety of overall system. Figure 1-1 shows a traction inverter block diagram.

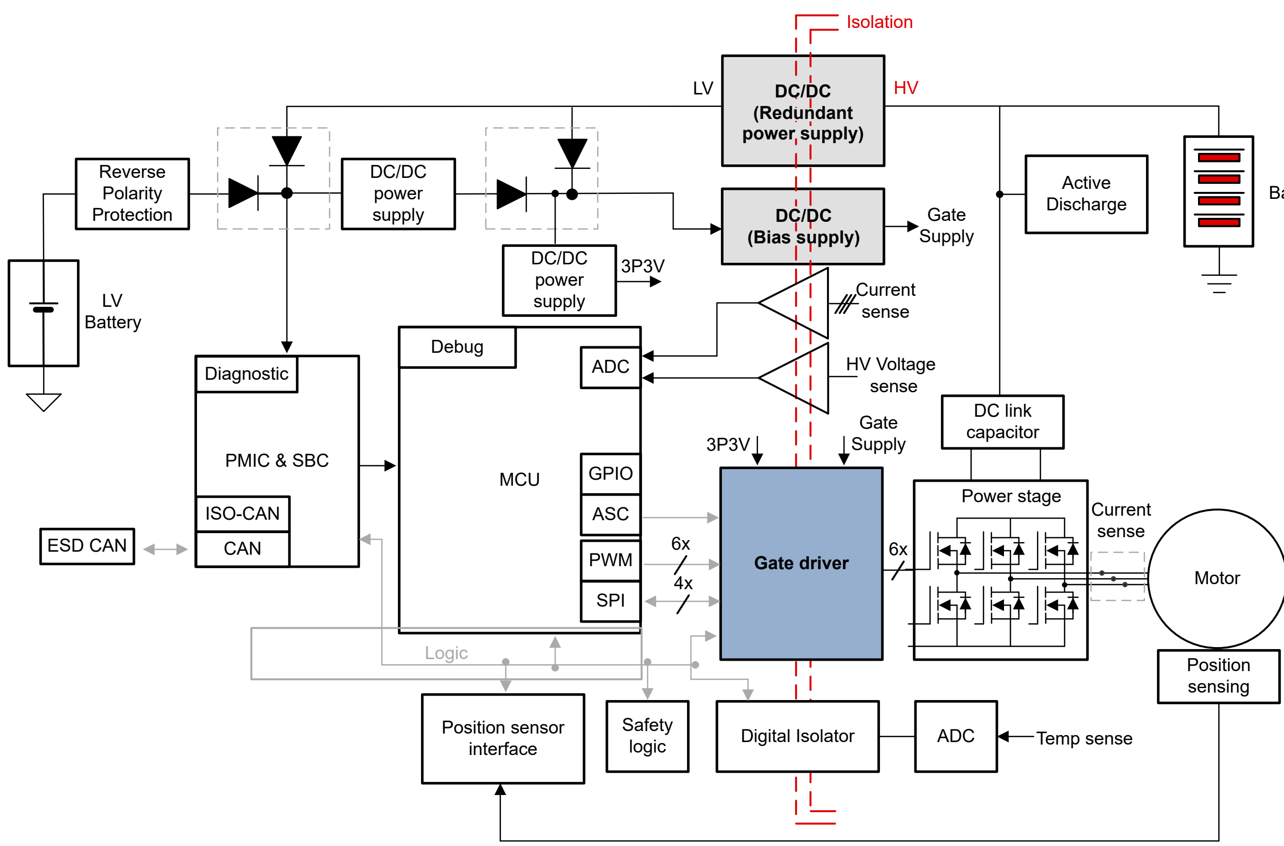

Figure 1-1. Traction Inverter Block Diagram

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 HEV and EV. Although there are some systems with 48V as a LV battery, this paper focuses on the 12V battery system. However, these architectures can be still relevant for 48V LV 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 LV 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 12V LV 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 LV 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 an HV battery as a power source in HEV and EV. As an HV battery, 400V and 800V voltage batteries are the most common in HEVs and EVs. The isolated bias supply connected to the HV battery needs to support a wider input voltage range. The need for wide input voltage range support is similar to the LV battery: SOC and load dump scenarios of the HV 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 HV 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	20–100W	2–50W	2–50W	2–50W	50–150W

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

2 Pre-Regulator Requirement

The need for a pre-regulator circuit for the isolated bias power supply device depends whether or not the circuit works for a wide input voltage range. Considering an input voltage range between 8V–16V, as an example for the 12V LV battery depending on SOC, the device used for bias power supply must function over this whole voltage range. Otherwise, a pre-regulator is needed. Apart from the wide input voltage range capability of bias power devices, other factors like line regulation and load regulation also influence the need for the pre-regulator circuit.

Section 2.1 shows different bias supply architectures including the use of a pre-regulator. In Section 3 onwards, pre-regulators are excluded from the block diagrams for clarity. Since there are multiple topologies and multiple associated devices which can be used in the same architectures, a pre-regulator is not always needed.

Table 2-1. Texas Instruments Pre-Regulator Devices

	LM5155x-Q1 Controller	LM5156x-Q1 Controller	LM5157x-Q1 Converter	LM5158x-Q1 Converter
Input voltage range	3.5V–45V	3.5V–60V	2.9V–45V	3.2V–60V
Output Current	1.5A peak standard MOSFET driver	1.5A peak standard MOSFET driver	Maximum 6.5A	Maximum 3.2A

2.1 Pre-Regulator at Low-Voltage Battery

With a 12V LV battery, the converters most commonly used as pre-regulators are single-ended primary-inductor converter (SEPIC), buck-boost converters, and flyback converters. These converters work for a wide input voltage range and provide a stable output voltage as an input to the isolated bias power supply devices. Quite often along with isolated bias power supply for gate drivers, the output voltage rail of these pre-regulators are also used to supply other parts of the system like sensors, communication devices, and so forth.

2.1.1 Single Pre-Regulators Architecture

The use of a single pre-regulator is a cost-effective option since there is only one pre-regulator for both high- and low-side bias power supply devices. However, using a single pre-regulator can result in a single point failure in case of any issues in the pre-regulator circuit. This is not always the best choice from the functional safety point of view.

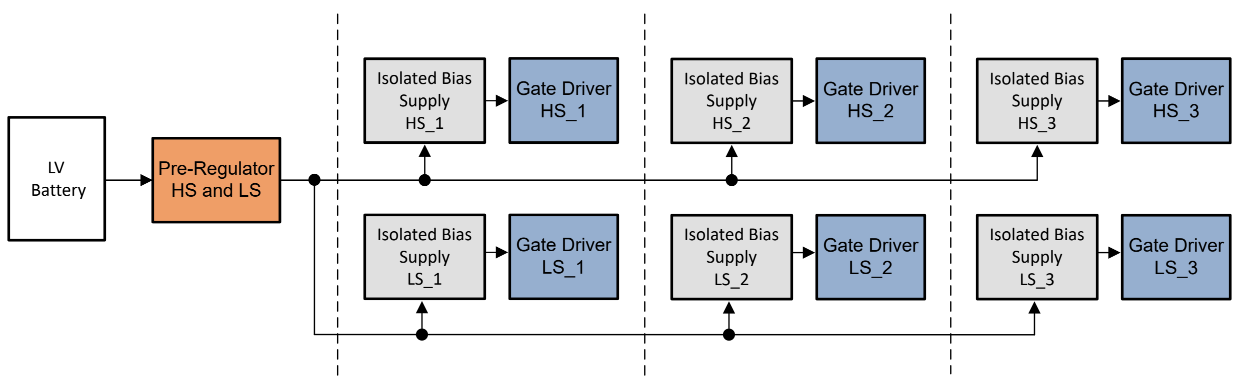

Figure 2-1. Single Pre-Regulator in a Fully-Distributed Architecture

2.1.2 Multiple Pre-Regulators Architecture

In an architecture with multiple pre-regulators, separate pre-regulators are used for high- and low-side bias power supply devices. This architecture can be preferable from a functional safety point of view. If one of the pre-regulator circuits has an issue or failure, the other pre-regulator circuit can still provide power to the low- or high-side gate drivers. A safe state can be achieved as all low-side or all high-side gate drivers continue to be controlled. Such architecture from a power perspective can help to achieve the safe state in the vehicle if an unfavorable event occurs.

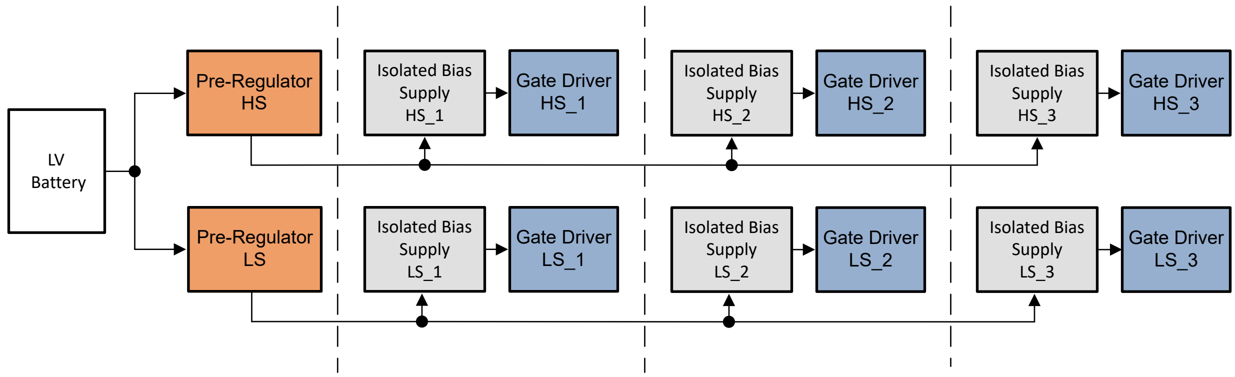

Figure 2-2. Two Pre-Regulators in a Fully-Distributed Architecture

2.2 Pre-Regulator From High-Voltage Battery

A flyback converter or controller connected with a 400V or 800V battery is used in two different ways. One way is as a pre-regulator to generate a particular voltage rail (12V, 15V, 24V, or so forth) and the other way is to be directly used as an isolated bias power supply for the gate drivers (Figure 6-1). While used as a pre-regulator, output voltage from HV flyback is used as the input voltage to isolated bias supply devices for gate drivers as shown in Figure 2-3.

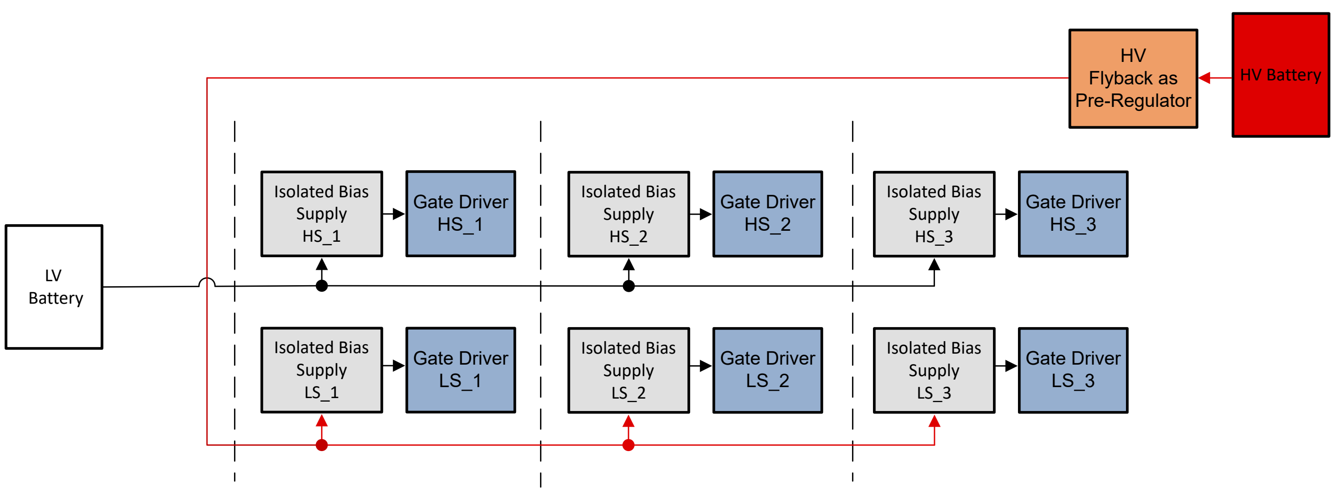

Figure 2-3. Pre-Regulator at High-Voltage Battery

3 Fully-Distributed Architecture

In a fully-distributed architecture of the traction inverter, each of the gate drivers is supplied by an individual isolated bias power supply device. That means for six gate drivers, six isolated bias supply devices are needed. Although this architecture is not necessarily a cost-effective option, using multiple power supply devices can help to increase the safety of the system.

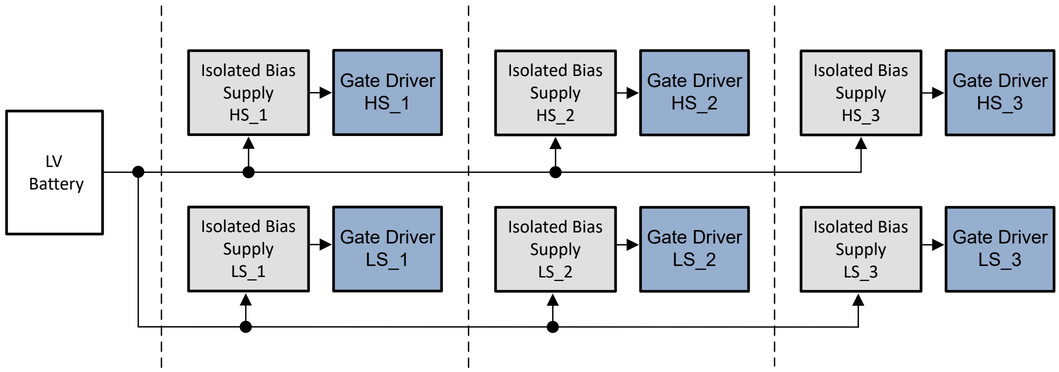

Figure 3-1. Fully-Distributed Architecture

Use of an integrated DC/DC transformer module can be the preferable choice for fully-distributed 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. Additionally, these integrated DC/DC modules need only 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. Figure 1-1 shows all variants and the technical specifications.

Table 3-1. 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

There are other topologies which can be used for a fully distributed type of architecture. Typical example of these topologies are LLC resonant, PSR-flyback (primary side regulated flyback) and push-pull. One of the advantages of these topologies is that have a capability to deliver more power compared to the integrated DC-DC modules. This is discussed in more detail in the next section.

4 Semi-Distributed Architecture

In semi-distributed architecture, multiple gate drivers share power from a single isolated bias power supply device. This architecture enables the cost saving of a separate device for each gate driver, but at the same time, failure in one device can stop the power supply to multiple gate drivers.

Within the semi-distributed architecture, there are two different possibilities. Figure 4-1 shows the first type of semi-distributed architecture. In this architecture, high-side gate drivers are supplied using three separate isolated bias power supply devices, for example using three integrated DC/DC modules. On the other side, all low-side gate drivers are supplied using a single isolated bias supply device. Some of the possible designs are LLC resonant (UCC25800-Q1), PSR-flyback (LM518x-Q1, LM2518x-Q1, LM515x-Q1, LM34xxx-Q1) and push-pull (SN650x-Q1) topology-based devices, which can deliver the required power to multiple gate drivers making these devices an excellent choice for semi-distributed architectures. While supplying multiple gate drivers using one device, the secondary side of the transformer (Pre:Sec = 1:3) has multiple windings, as an example - three secondary windings for three gate drivers.

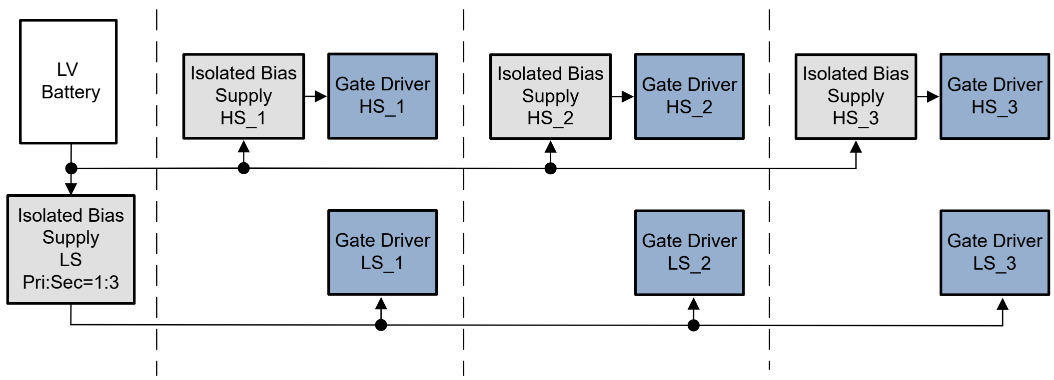

Figure 4-1. Semi-Distributed Architecture at Low Side Only

Figure 4-2 shows the second type of semi-distributed architecture where both high-side and low-side gate drivers are supplied using two single isolated bias supply circuits. In each of these circuits (high side and low side), there is one transformer with multiple secondary windings. This architecture requires only two isolated bias power devices, which can be a cost-effective option. Unlike the low side, which has common ground, the high-side voltage reference is floating. Therefore, due to cross-coupling and so forth, the stability of a multi-winding transformer at the high side is challenging.

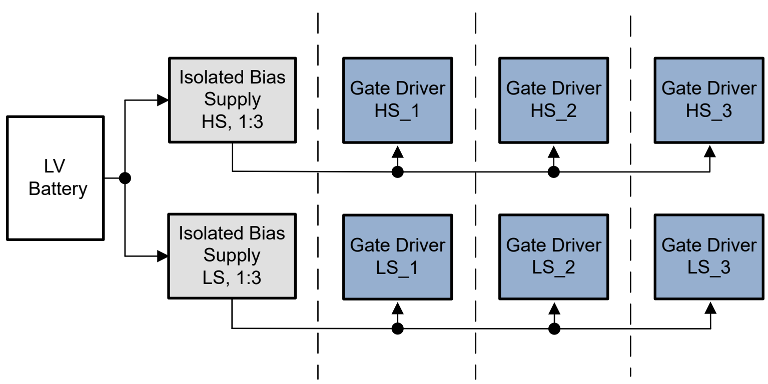

Figure 4-2. Semi-Distributed Architecture at High Side and Low Side

5 Centralized Architecture

In centralized architecture, all high-side and low-side gate drivers are supplied using a single isolated bias power supply device. This can be the most cost-effective design. On the other side, a failure in this device results into a single point failure and all gate drivers lose the power supply at the same time. Another challenge with this type of architecture is to design a transformer with 6 secondary windings (Pri:Sec = 1:6) and complex PCB layout due to long PCB traces. Therefore, it is difficult to achieve tight voltage regulation in this architecture. Centralized architecture is not commonly used in traction inverters.

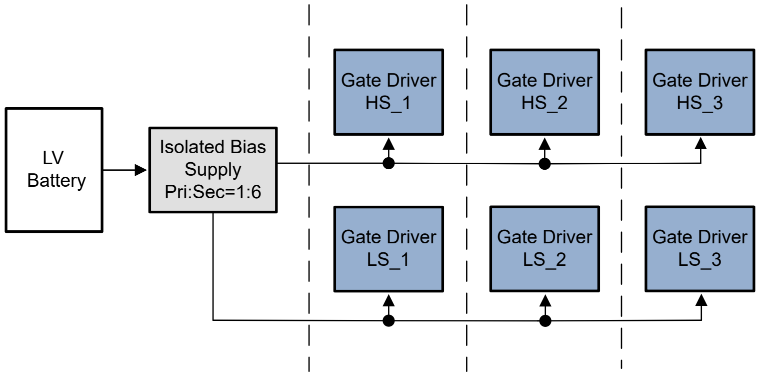

Figure 5-1. Centralized Architecture

6 Redundancy in Isolated Bias Power Supply Architectures

Functional safety is an important topic in the automotive industry. To make the whole system more reliable, there is a need for redundant power supply. This means that isolated bias supplies are getting power from both HV and LV batteries. Redundancy can be provided either to all devices or only to the low side or high side. Depending on the functional safety concept, providing the redundant supply only to one side can be sufficient to achieve the safe state.

6.1 No Redundancy

Figure 6-1 shows the architecture where both LV and HV batteries are used for providing the power to isolated bias supply devices. The low-side gate drivers are supplied from the HV and the high-side gate drivers from the LV battery. A vice-versa combination is also possible. In both cases there is no redundancy for the gate drivers, but there is a lower risk that both high-side and low-side gate drivers lose the supply at the same time. In case of losing connection or supply from one battery, either low-side or high-side gate drivers can still be powered.

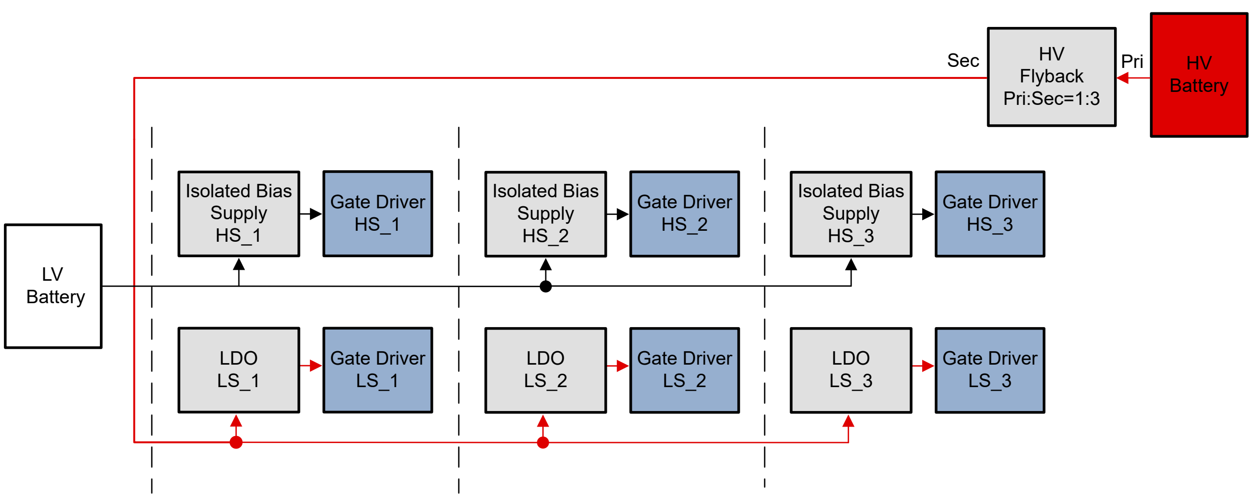

Figure 6-1. No Redundancy While Using LV and HV Batteries

6.2 Redundancy to all Devices

In such architecture, both LV and HV batteries are used to supply power to all gate drivers in the system, which provides redundancy to all of them. In this redundant architecture, in case of a failure either from LV or HV batteries, all the gate drivers are still powered from the other battery. In general, the gate drivers are primarily powered using the LV battery. Whereas, the HV battery is used to provide redundancy. This redundant architecture has better reliability from the functional safety point of view but the design adds additional cost in the system.

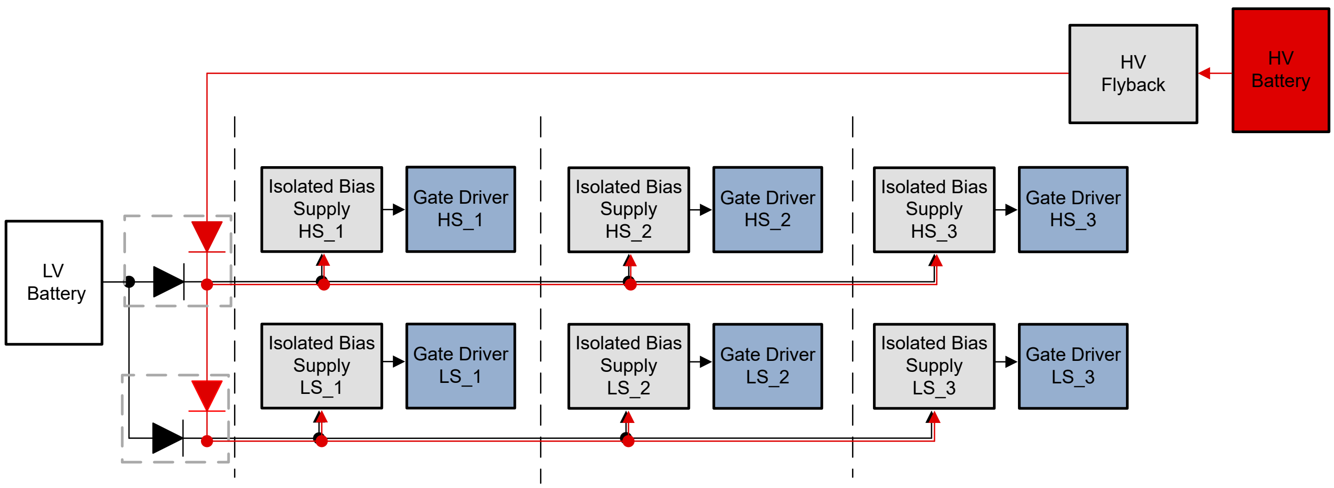

Figure 6-2. Redundancy to the all Devices in Fully-Distributed Architecture

6.3 Redundancy to Low Side Only

Figure 6-3 shows the low-side gate drivers are powered from both the LV and the HV battery. In this method, the LV battery is used as a main power supply, while the HV battery is used to provide the redundancy to the low-side gate drivers. On the other side, the high-side gate drivers are powered only from the LV battery. Having redundancy either to the low-side or high-side gate drivers can help to achieve one of the possible safe states (for example: active short circuit). If there is a failure at the LV battery, the low-side gate drivers are still powered from the HV battery. Compared to the previous architecture, where all gate drivers have the redundant power supply, this architecture is more cost-effective and might be sufficient to fulfill functional safety requirements.

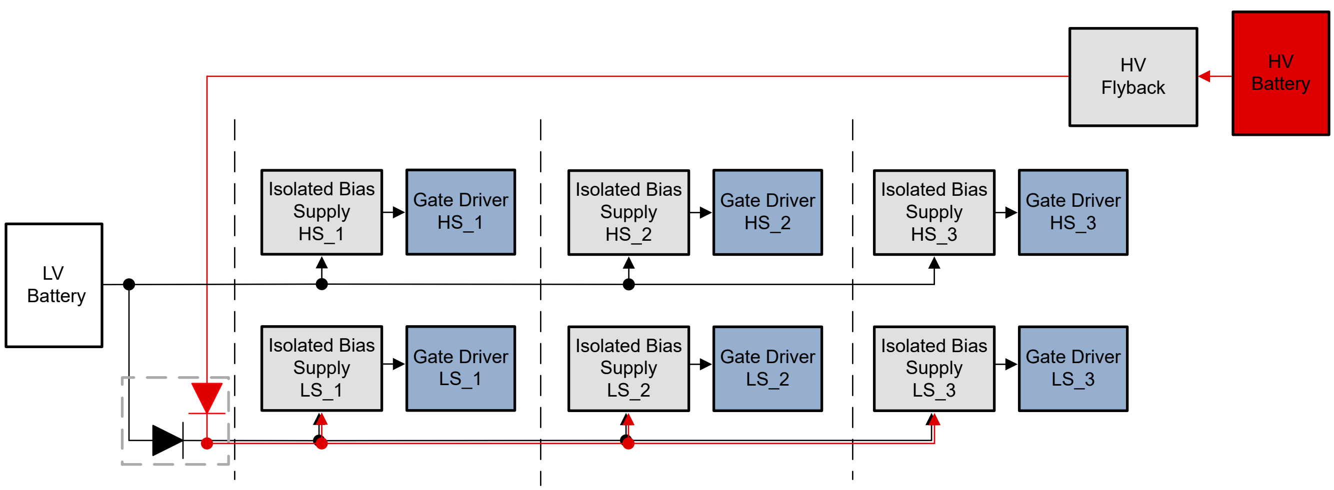

Figure 6-3. Redundancy Only at the Low Side in Fully-Distributed Architecture

6.4 Redundancy to High Side Only

Similar to the redundancy only to the low side gate drivers, the same scenario is possible to provide redundancy only to the high-side gate drivers. Figure 6-4 shows this type of architecture.

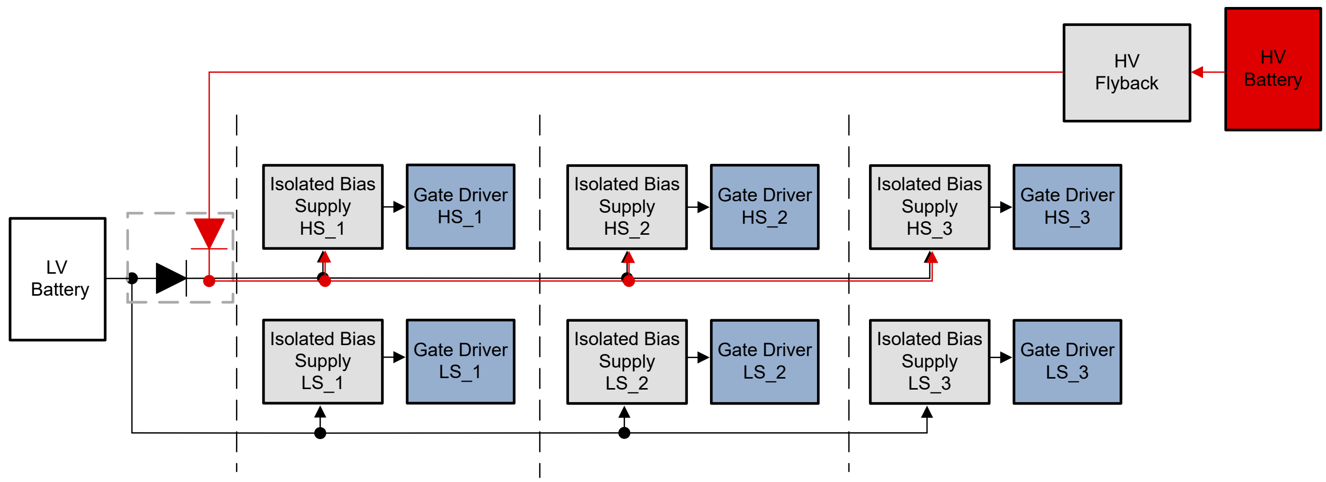

Figure 6-4. Redundancy Only at the High Side in Fully-Distributed Architecture

7 Summary

Isolated bias supply is an important part of every traction inverter system. There are several isolated bias power supply architectures for traction inverters 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
HV	High voltage
HS	High side
LDO	Low-dropout regulator
LLC	Inductor-inductor capacitor
LS	Low side
LV	Low voltage
OEM	Original equipment manufacturer
Pri	Primary
PSR	Primary side regulated
Sec	Secondary
SEPIC	Single ended primary inductor converter
SOC	State of charge
$\mathbf{V_{IN}}$	Input voltage
$\mathbf{V_{OUT}}$	Output voltage